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NASP RE-ENTRY PROFILE: EFFECTS OF LOW-LEVEL +Gz ON REACTION TIME, KEYPAD ENTRY, AND REACH ERROR

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The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Regulation 169-3.

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Thomas J. Moore

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13. ABSTRACT (Maximum 200 words) The National Aerospace Plane (NASP) is projected to have a re-entry profile which may generate a maximum of +2.5gz for up to 30 minutes. Very little is known about the effects of this type of acceleration profile on human performance. Thus, 8 subjects were exposed to +2gz for 40 minutes on the DES centrifuge, during which time they performed a choice reaction time task, a keypad entry task, and a reach task. The tasks were based on one of many preliminary NASP cockpit designs. Results indicated that for simple reaction time tasks no performance decrements were found; in fact a slight increase in performance occurred. For the keypad task, however, performance decrements were found throughout the entire profile. The reach task showed decrements early in the exposure, but towards the end performance reached baseline levels. This suggests a "recalibration" of gross motor movement during long exposure to low-level acceleration. Results indicated that input devices which require large arm/hand movements should be mounted no farther than 21" from the floor and 35" away from the intersection of the seat back/pan of an ACES II-type seat. Keypad entry devices should have button sizes of at least 3/4" by 3/4", and should be mounted on a swivel mount to reduce uncomfortable wrist angles.

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PREFACE

This research was conducted as part of a larger program concerning human adaptation effects to long-term exposure to low-level acceleration, specifically as it may apply to space motion sickness. The results of this overall program will be outlined in a future report.

The authors would like to thank Greg Bathgate and Don McCollor of Systems Research Laboratories for their help in materials fabrication for this project, SSgt T.C. Cartwright and Bob Esken of the Armstrong Laboratory for their efforts in electronics and software development, and Jennifer Farrell of ASC/SDXE and Eureka Matsunaga of Rockwell International for their help in identifying and selecting the preliminary NASP cockpit design for use in this study.

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INTRODUCTION

Nature of the Problem

Various aerospace companies, along with a consortium of Department of Defense agencies, have been developing preliminary National Aerospace Plane (NASP) concept designs concerning the optimum placement of input devices within the cockpit. The major questions which concerned the personnel within our laboratory were related to the human factors issues centered on the re-entry profile of the NASP. It was projected that crew members could be subjected to a maximum of +2.5gz for up to 30 minutes at a time (worst-case scenario) during re-entry from orbital flight. Basically, questions centered around the performance aspects of crew members during a re-entry profile of this type. Cockpit designers wanted to know the effects of this low-level, long-term exposure to acceleration on both fine motor control (keypad entry, button presses) and gross motor control (reaching for multi-function displays, etc.). However, as will be seen below, performance data obtained from subjects undergoing high-g profiles of less than +3gz are scant, and the data that do exist are primarily focused on visual decrements, memory deficits, and effects on fine motor control and/or flight stick inputs. There is virtually no empirical information concerning gross motor control within a large reach envelope under increased +gz.

Literature Review: Available Information

There are a few review articles that summarize the available research on human performance under high-g. An early review was conducted by Grether in 1971. He summarized the evidence showing that tracking and flight control exhibits progressive impairment as +gz increases, and also maintained that early research suggested that manual output functions may be more susceptible to acceleration-induced mechanical impairment than intellectual/central nervous system impairment (at least at lower +gz levels). Voge (1980) also published a review, which centered mostly on reaction times (RTs) during complex mental tasks which required fine motor control outputs from subjects, decreases in sensory and central nervous system efficiency, and effects on visual function under increased +gz (increased absolute thresholds, decreases in brightness discrimination and visual acuity, and difficulty in instrument reading). In 1991, von Gierke, McCloskey, and Albery provided a review which focused mainly on visual decrements, human memory and central processing decrements, manual control decrements (predominantly tracking performance), and changes in time and mass estimation. A quick inspection of Table 1 shows that *all* of the experimental results reviewed were obtained from acceleration profiles equal to or greater than +3gz, and *none* of the available literature provided information on gross motor movements under any +gz level. However, it should be noted here that anecdotal evidence is abundant. For example, it's been known for some time that at +3gz and above it is virtually impossible to raise onself from a sitting position, let alone control the gross motion of an arm or leg (Fraser, 1973). There is no information, however, concerning gross motor movements in the +1.5gz to +3gz range.

TABLE 1. Acceleration and Human Performance Literature Review (adapted from von Gierke, McCloskey, and Albery, 1991).

Category	G level	Type of decrement	References
Vision:	$>4\text{-}5 + G_z$	Visual dimming, blackout	Kerr & Russell (1944) Hallenbeck (1946)
	$>3\text{-}4 + G_z$	Detection thresholds increased for foveal and peripheral vision	White (1960) White & Monty (1965)
	$>4\text{-}5 + G_z$	Decreased contrast sensitivity	White (1958) Braunstein & White (1962)
	$>4\text{-}5 + G_z$	Increased reaction times to visual discrimination	Canfield, Comrey, & Wilson (1949)
	$>3\text{-}5 + G_z$	Increased errors in dial reading	Warrick & Lund (1946)
Memory and central processing:			
	$>6\text{-}7 + G_z$	Increased errors in a memory task	Chambers (1961; 1963) Chambers & Hitchcock (1963)
	$>3 + G_z$	Increased reaction times to a multiplication task	Frankenhauser (1945)
	$>5\text{-}6 + G_z$	Increased subjective ratings of workload	Albery *et al.* (1985)
Manual control:			
	$>4 + G_z$ $>4 \pm G_x$	Increased tracking error with *lightly* damped control characteristics	Creer (1962)
	$>6 + G_z$ $>14 + G_x$	Increased tracking error with *heavily* damped control characteristics	Creer (1962)
	$>5 + G_z$	Increased tracking error	Burton & Jaggars (1974) Little *et al.* (1968) Piranian (1982) Loose *et al.* (1976)
Time and mass estimation:			
	$>6 + G_z$	Time underestimated during long tasks	Frazier *et al.* (1990) Popper *et al.* (1990)
	$>4 + G_z$	Increased error for weight estimation	Darwood *et al.* (1990)

Choosing the Tasks and the +Gz-Profile for the Present Study

A review article dealing with test and evaluation metrics for use in sustained high-g environments has recently been published (McCloskey, Tripp, Chelette, and Popper, 1992). The authors make a case that the types of performance tasks for use under increased +gz are as numerous as there are tasks available. It seems that the development and proliferation of different performance tasks with no standardization increases with the passage of time, with the exception of recent task batteries which use simplified versions (part-tasks) of complicated flight missions.

We chose tasks that potentially had the most relevance to the preliminary NASP cockpit designs and re-entry profile: 1) a simple choice reaction time task; 2) a more complex keypad entry task; and 3) a gross motor control reach task. The first task was chosen because it has been used in numerous high-g investigations in the past, and provides an almost "pure" fine motor control representation (Domaszuk and Wojtkowiak, 1975; Popper, Repperger, McCloskey, and Tripp, 1992). The second task was chosen to represent a more complicated fine motor control task which requires a great deal more mental investment to complete than does the first task. In addition, this task is quite representative of the types of keypad entries required of crew members during actual flight. The third task was chosen to provide badly needed information concerning gross motor control within the +1.5gz to +3gz range.

The actual experimental set-up was based on a "sample" NASP cockpit layout blueprint (one of many possible preliminary designs) which dictated the location of the two fine motor control tasks (both input devices mounted between the knees) as well as the reach distances/positions for the gross motor control task (five different multi-function display units located in 3-dimensional space around the subject). This experimental set-up is explained in more detail in the Methods section.

Finally, the +gz profile chosen was one of 40 minutes duration with a maximum g-level of +2gz. Recall that the literature reviewed had the lowest g-level of +3gz, while the maximum g-level of the projected NASP profile would be +2.5gz. We chose +2gz as the experimental condition. Any performance decrements at +2gz would theoretically also be present at any g-level above it, and probably to a greater degree. In addition, +2gz was approximately in the middle of the +1.5gz to +3gz range for which there is no gross motor movement information. We chose 40 minutes duration in order to both encompass the projected maximum of 30 minutes, and to go beyond it.

Possible Hypotheses

The simplest fine motor control task, choice reaction time, exhibits a fairly high level of performance stability in biodynamic environments (Popper et al., 1992). This task becomes almost automatic with practice for most subjects. With a task such as this, we should be able to obtain a "pure" fine motor control response function with almost no memory involvement. If this is the case, traditional theory would suggest that as g is increased from normal 1g to +2gz, it should be more difficult for subjects to maintain performance levels simply because of the additional perceived weight of the hands and fingers, *not* because of interference with central memory functions (Fraser, 1973). On the other hand, an "arousal" effect has been widely documented for simplistic tasks under different types of environmental stressors. This is related to the classic "inverted-U" phenomenon which states that each human endeavor requires an individualized optimum level of arousal to reach optimum performance levels (Yerkes and Dodson, 1908). For easy tasks, more arousal would be needed for optimum performance than for more difficult tasks. Thus, a decrement in performance with the simple choice reaction time task could be explained by a perceived increase in hand/finger weight, while conversely, an improvement in performance could be explained by the inverted-U phenomenon. It is not known which of these patterns will emerge from the data.

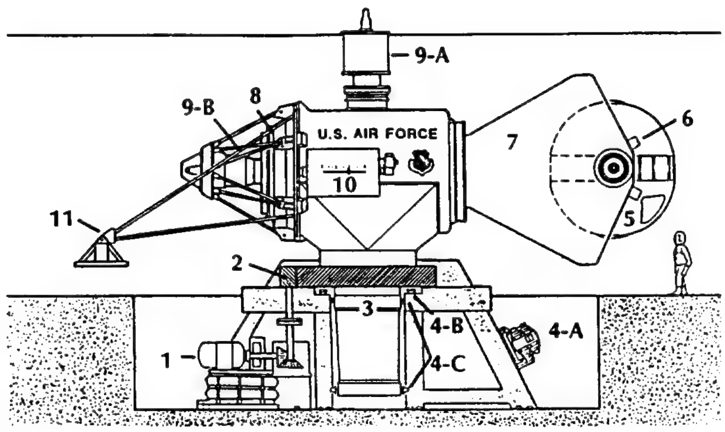
For the more difficult keypad entry task, both increased weight of the hand/fingers and central memory functions should be called into play. Thus, decrements in performance are expected during +2gz not found under normal +1gz conditions. In addition, the inverted-U theory may also be invoked to explain performance decrements, in that arousal under +2gz is too high for optimal performance. If so, there may be some performance level adjustments as the length of time at +2gz increases (i.e., as subjects pass through the 40 minute exposure).

Finally, for the gross motor movement reach task, initial overshoots/undershoots of the arm/hand in 3-dimensional space are expected. This will probably occur early in the +2gz exposure before subjects "recalibrate" their large arm movements to accommodate for the increased g. In addition, larger errors in hand/arm movements should be found for the multi-function displays located at the extreme ends of the vertical and horizontal planes (i.e., extreme left-right and up-down). It should also take subjects longer to move their arms/hands to these "extremes," which should be reflected in longer reaction times for those particular multi-function displays.

METHODS

High-G Simulator

All experimental runs were conducted with the Dynamic Environment Simulator (DES), a man-rated centrifuge located at Wright-Patterson AFB, Ohio (Figure 1).



1. Main Arm Drive Motor
2. Drive Pinion
3. Main Rotating Trunion and Bull Gear
4. Hydrostatic Bearing System
   - 4-A Hydraulic Pumps
   - 4-B Thrust Pad
   - 4-C Upper and Lower Radial Pads
5. Cab
6. Cab Drive Motor
7. Fork
8. Fork Drive Motor
9. Slip Ring Assemblies
   - 9-A Main Arm Axis
   - 9-B Fork Axis
10. Motor Driven Counterweight
11. Aft-Mounted Experimental Platform

FIGURE 1. The Dynamic Environment Simulator (DES) Centrifuge.

Experimental Station

The entire experimental station, located inside the subject cab of the DES, is shown in Figure 2. As can be seen, a row of multi-function displays (MFDs) were mounted on a wooden brace crossways above a center-mounted, between-the-knees keypad entry device and a four-button response pad console. An additional MFD was located at the far right, to the side of the right-hand mounted flight stick. A throttle handle was provided at the left of the picture, and rudder pedals below and to the back of the row of MFDs can be seen. Lastly, a visual display screen was located above the row of MFDs. Appendix A1 shows the engineering drawings of the dimensions of the seat used; Appendix A2 shows the dimensions of the keypad entry device and four-button response pad console; Appendix A3 shows the dimensions of the MFD mounts; Appendix A4 shows the reference of the seat to the entry devices and the MFDs; and Appendix A5 shows global measurements of the entire experimental station.

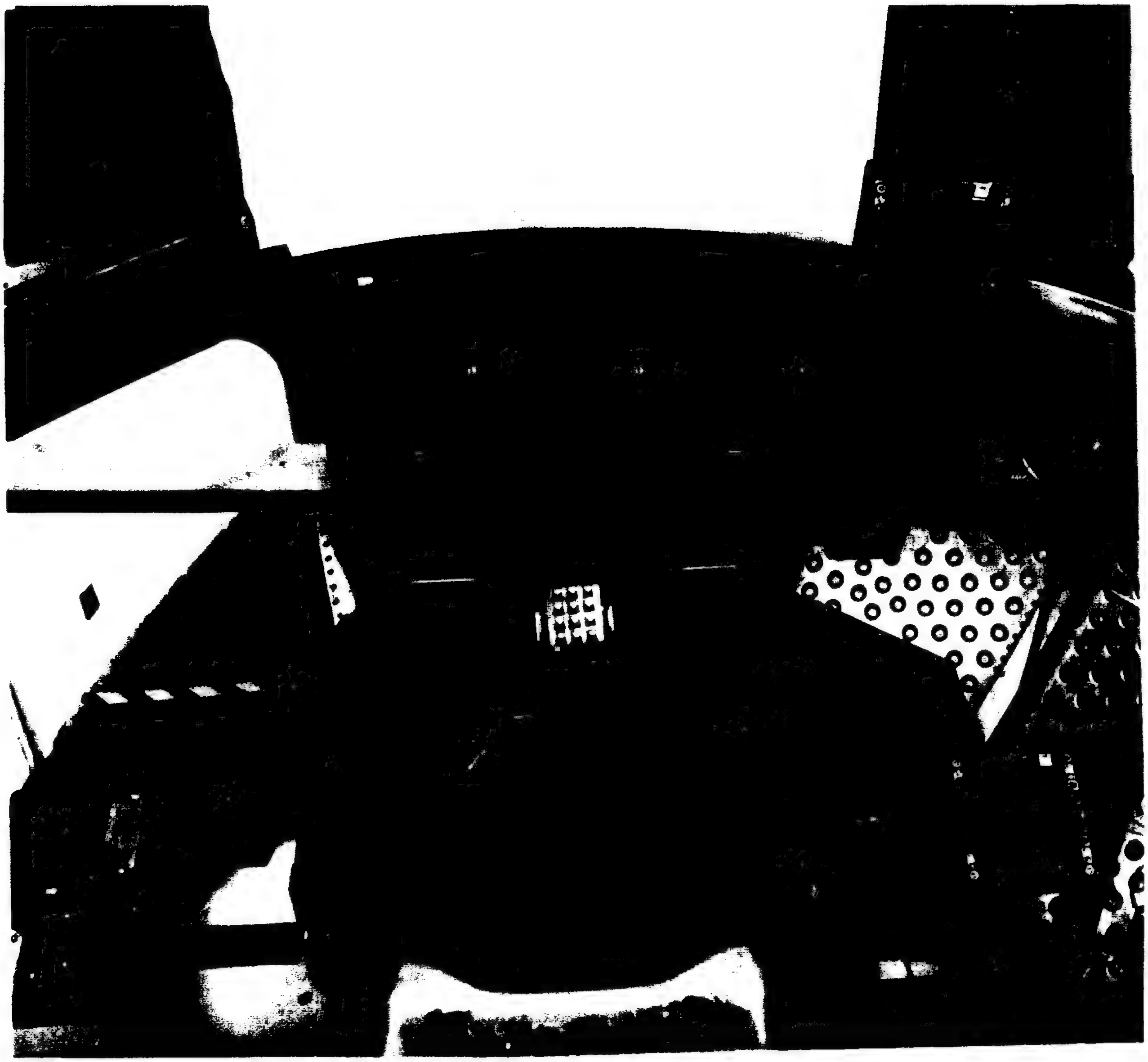


FIGURE 2. Experimental Station Inside the Subject Cab of the DES Centrifuge.

Performance Tasks

Choice Reaction Time Task

The choice reaction time task required subjects to monitor the forward-mounted visual display screen for the occurrence of lighted circles. There were four circles presented, and the number and location of the circles which were lighted at any given time were randomized (see Figure 3). Either one, two, or three circles could be lighted during any trial. Subjects were then required to depress the corresponding number and location of buttons on a four-button response pad located on the center-mounted console. Subjects used the first two fingers of each hand to respond.

For each session, there were 45 single trials where either one, two, or three circles were lighted. The presentation of these stimuli were pseudo-randomized to assure 15 trials for each of the one, two, or three circles lighted conditions. Any button presses that occurred more than 2000 msec after the lights came on were deemed an error, as well as any responses faster than 100 msec. If two button presses were required simultaneously (the two or three light condition), subjects had to press the buttons within 50 msec of each other or that trial was also marked as an error. Time between single trials was programmed to occur randomly between 500 and 1000 msec to reduce response rhythm and prediction of stimulus occurrence.

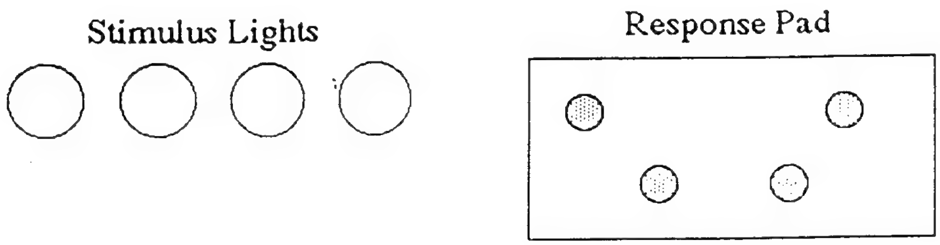


FIGURE 3. The Choice Reaction Time Task.

Keypad Entry Task

A six-digit entry number appeared on the visual display screen, and subjects were required to enter that number on the response keypad, and then press the pound-sign key (#) to indicate closure for that trial. The keypad entry response device was a standard push-button pad taken from a telephone (see Figure 4). Each subject used their dominant hand. There were 30 single trials per session. Each single trial consisted of the presentation of a totally random six-digit number, the number entered on the keypad, and a pound-sign key stroke. Errors included taking more than 6000 msec to complete the trial, or entering a wrong number during keypad entry. There was no allowance to correct or erase an incorrect keystroke. The six-digit numbers were presented randomly between 350 and 750 msec after the pound-sign keystroke to once again control for response rhythm and prediction of stimulus occurrence.

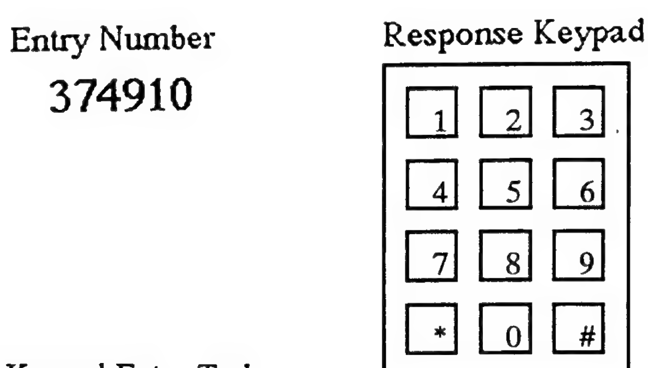


FIGURE 4. The Keypad Entry Task.

The Multi-Function Display (MFD) Task

There were two different sets of data collected from this task. The first was the amount of time it took a subject to press a bezel button located on one of the 5 MFDs from a baseline position of having the right hand on the flight stick. The second was 3-dimensional (3-d) data collected concerning the movement path of the hand through space during these bezel button presses. A visual display corresponding to the spatial location of each of the 5 MFDs was presented on the visual display screen (see Figure 5). During each single trial, only one of the boxes on the screen which corresponded to one of the MFDs was lighted. The subject was required to pull a trigger located on the flight stick at the onset of light, and then as quickly as possible reach out to press the bezel button located on that MFD. Thus, reaction time was collected from the onset of the light to the press of the bezel button. However, the 3-d data were collected from the time of the trigger pull on the stick to the press of the bezel button.

Three-dimensional binary (digital) movement data (x, y, and z axes) were collected using an Ascension Technology Corporation 6-degree-of-freedom input device known as The Bird™, via an RS 232 port connected to a host computer. The transmitter was located at the bottom of the wooden MFD mount, and the receiver was strapped to the back of the subject's right hand. The transmitter provided a DC electromagnetic field, and the receiver provided position information concerning the hand within that field (see Appendix B).

There were a total of 15 single trials for each session, 3 trials for each of the 5 MFDs. Errors were recorded if the subject took longer than 5000 msec to push the bezel button after the trigger pull, or if the wrong bezel button was pushed.

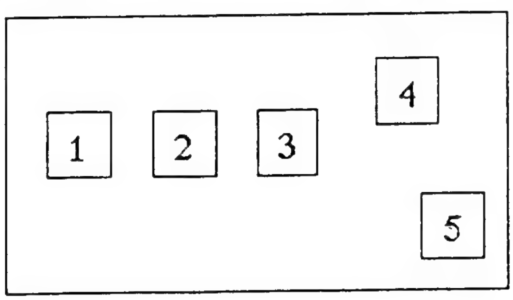


FIGURE 5. The Multi-Function Display (MFD) Task.

Subjects

There were 5 males and 3 females who participated in this study. Ages ranged from 26 to 43 years. All had passed extensive physical examinations for inclusion on the Sustained Acceleration Subject Panel. Informed consent for the study was obtained from all 8 subjects.

All 8 subjects finished the study. Complete records were obtained from all subjects throughout the experiment except for the 3-d motion data due to technical difficulties; complete 3-d data sets were obtained from only 4 subjects.

Experimental Design

Training

The choice reaction time task and the keypad entry task required extensive training during static conditions before subjects exhibited stable, repeatable performance. The MFD task, as determined by a short pilot study, did not require training since no improvement in performance was obtained by repeated exposures to the task. To obtain an MFD baseline from which to normalize the experimental data, each subject performed three task sessions (15 single trials in each session) immediately before the +2gz exposure was to begin, and the average of the three sessions was used as the baseline value.

Choice Reaction Time Task. The reaction times (RTs) and error rates obtained from this task exhibited a large practice effect during static 1g training (Figure 6a and 6b). As can be seen, it took subjects between 34 and 61 practice sessions to reach asymptotic performance levels (a session was defined as a collection of 45 single trials performed in one sitting). For RTs, average asymptotic performance was a mean of 469 msec with a standard deviation of 51 msec. For number of errors, average asymptotic performance was a mean of 1.4 errors with a standard deviation of 2. Each subject's last practice session average was used as the baseline from which experimental data were normalized (see Results Section, below).

Keypad Entry Task. The RTs and error rates obtained from this task also exhibited large practice effects during static 1g training (Figure 7a and 7b). Again, it took subjects anywhere from 34 to 61 practice sessions to reach asymptotic performance levels (a session was defined as a collection of 30 single trials performed in one sitting). For RTs, average asymptotic performance was a mean of 3514 msec with a standard deviation of 675 msec. For number of errors, average asymptotic performance was a mean of 2.6 errors with a standard deviation of 2.5. Once again, each subject's last practice session average was used as the baseline from which experimental data were normalized.

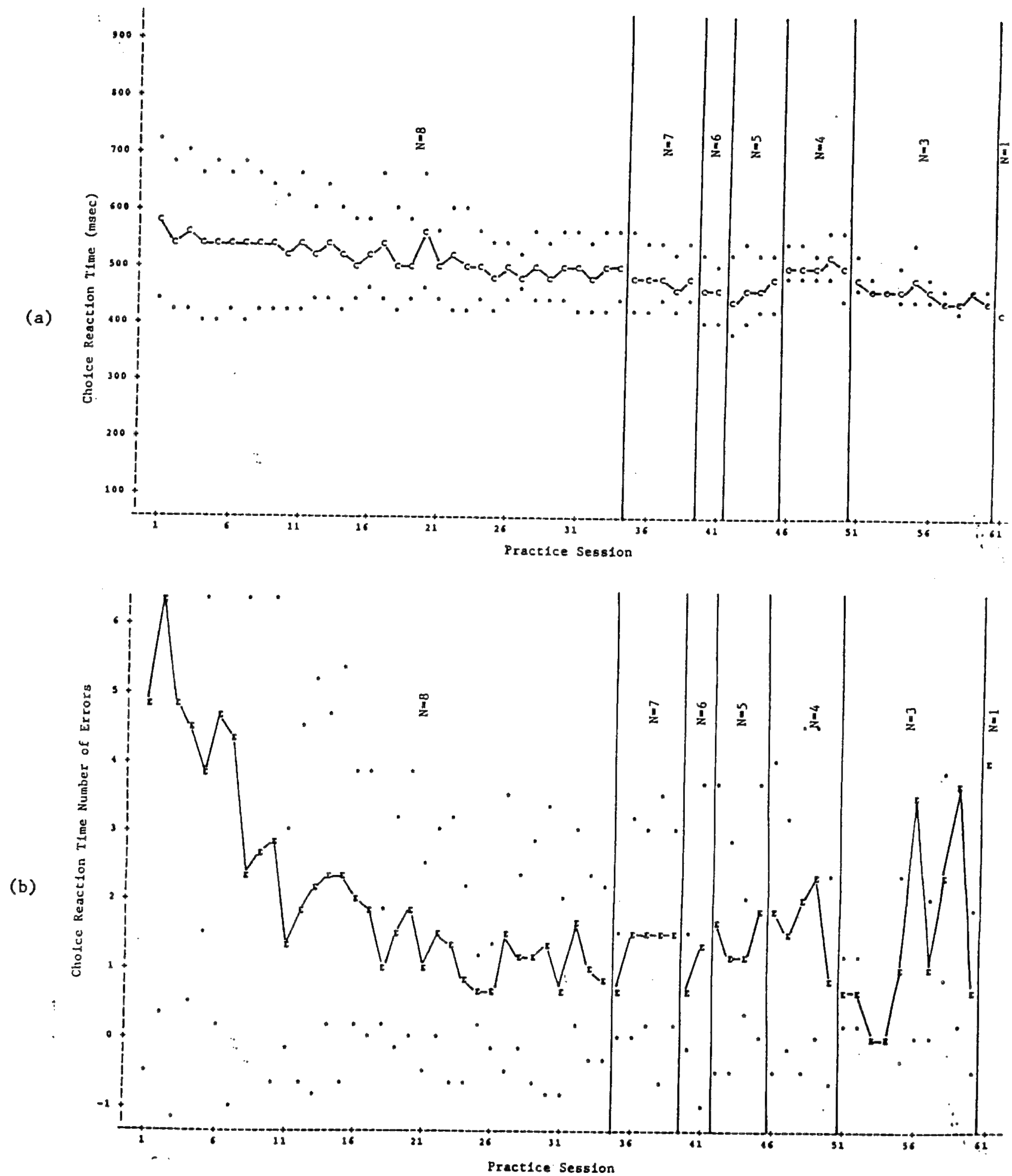


FIGURE 6. Choice Reaction Time Practice Data -- (a) RTs; (b) number of errors.

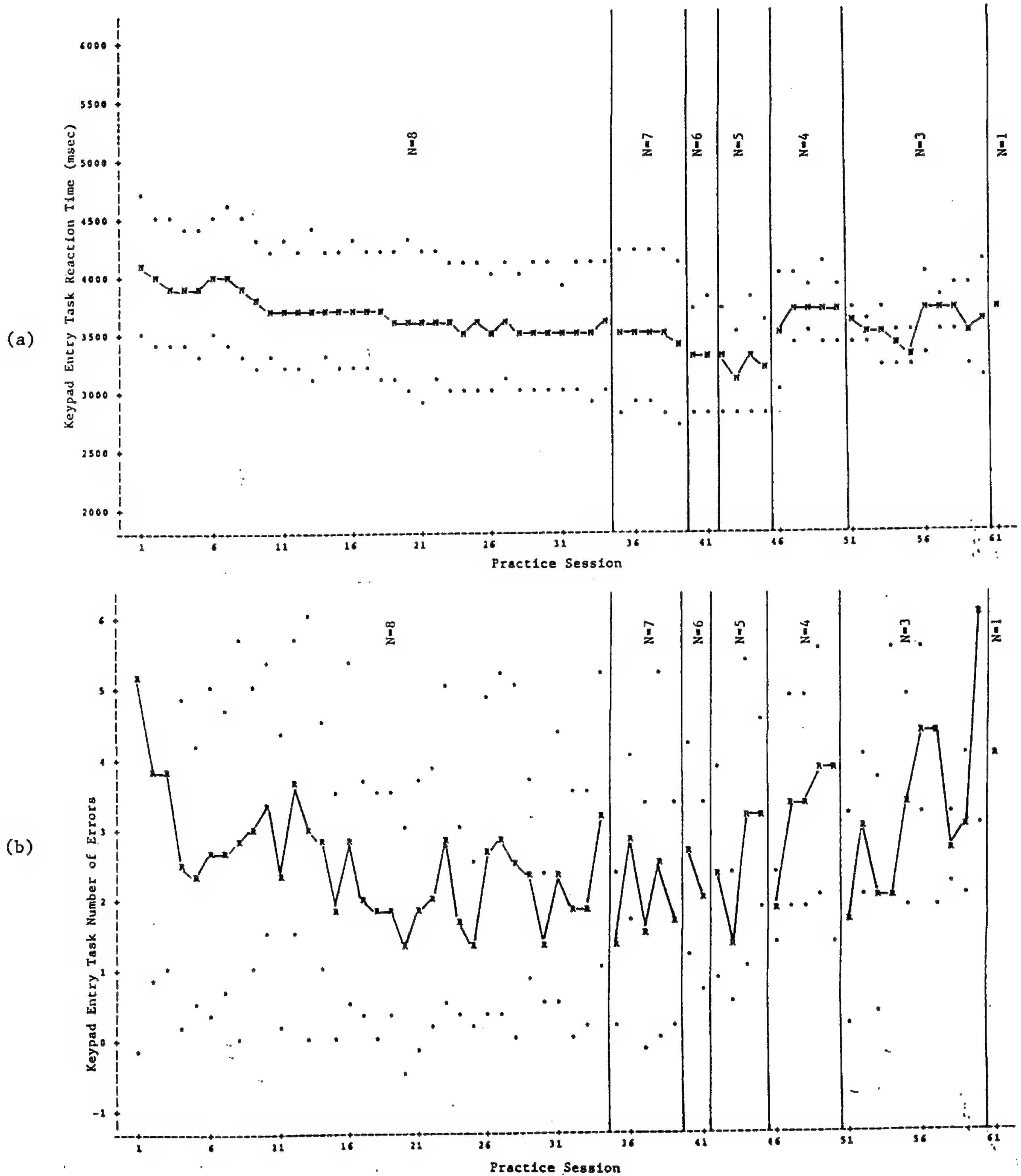
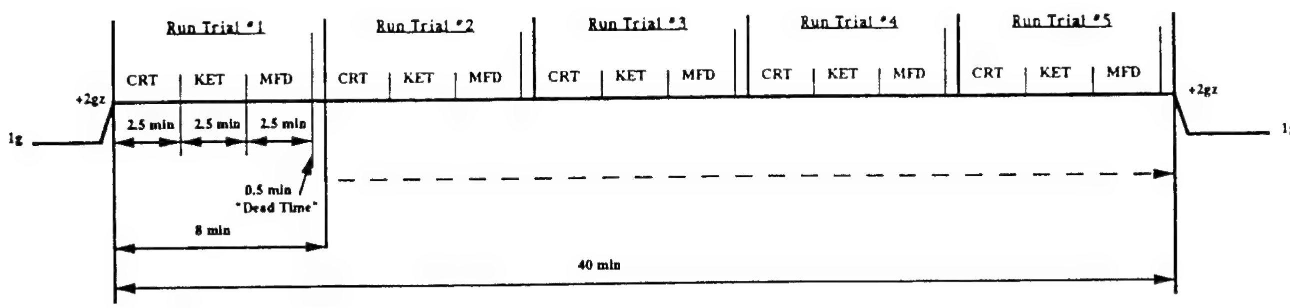


FIGURE 7. Keypad Entry Task Practice Data -- (a) RTs; (b) number of errors.

Task Presentation During the +2gz Profile

The tasks were always presented in the following order: 1) choice reaction time task, 2) keypad entry task, and 3) MFD task. One pass through this order was deemed a data run trial number and 5 run trials occurred throughout the +2gz exposure. Each of the five run trials began exactly 8 minutes apart, meaning that the time between the first to second, second to third, and so on, choice reaction time task was 8 minutes, as well as the keypad entry task and the MFD task. The order of the tasks was not randomized because each task was considered and analyzed separately from the others, and precise timing "hacks" of 8 minutes for each task was essential in answering questions concerning the effects of accumulated exposure to the +2gz stress. Figure 8 shows the progression of the design across time.



CRT = Choice Reaction Task; KET = Keypad Entry Task; MFD = Multi-Function Display Task

FIGURE 8. Task Presentation Across +2gz Exposure.

The +2gz exposure had an onset-offset rate of 0.5g/sec, which means subjects arrived at +2gz from 1g in 2 sec (and reached 1 g from +2gz in 2 sec). The +2gz exposure lasted 40 min. Thus, as can be derived from Figure 8, above, subjects performed the choice reaction time task at 0.0 min, 8.0 min, 16.0 min, 24 min, and 32 min into the 40 min +2gz exposure. Subjects performed the keypad entry task at 2.5 min, 10.5 min, 18.5 min, 26.5 min, and 34.5 min into the 40 min +2gz exposure. And finally, subjects performed the MFD task at 5 min, 13.0 min, 21 min, 29 min, and 37 min into the 40 min +2gz exposure. If subjects finished a task session before the next was to begin, the screen went blank and there was no task presentation. In addition, within each of the 5 run trials, there was 0.5 min worth of "dead time" after the MFD task, before the next run trial began.

Before each of the three tasks in a run trial began, the visual display screen showed the task stimuli along with a 15 second countdown. Thus, for the choice reaction time task, subjects were shown the four stimulus lights with a 15 sec counter superimposed on the scene; for the keypad entry task, subjects were shown a six-digit number with the 15 sec counter superimposed; and for the MFD task, subjects were shown the five boxes which corresponded to the spatial orientation of each MFD with a 15 sec counter superimposed. At the end of each 15 sec countdown, the screen went blank and the first single trial of the task was presented.

In addition, each subject was required to maintain a "baseline" body position during the time they were not performing any tasks. Specifically, each subject kept his or her right hand on the flight stick and the left hand on the throttle until the 15 second countdown for each task appeared on the screen. Subjects were then allowed to bring their hands inward toward the fine motor control input devices mounted between their knees. If they were to begin the MFD task, they kept their hands in the baseline position until the onset of the first button press. Both feet were to be kept on the rudder pedals with knees at a comfortable angle throughout the entire +2gz exposure. Each subject wore standard-issue flight suits, helmets, and boots. No gloves or anti-g suits were worn.

Finally, each subject underwent a detailed exit interview concerning the following topics: 1) body pain incidence and location, 2) disorientation (specific to short-arm rotation of the centrifuge, *not* the NASP), 3) fatigue, 4) increased weight of body parts, 5) design of the seat, 6) design of the keypad, 7) design of the four-button pad, 8) design of the MFDs, and 9) flight stick/throttle position.

Anthropometric Measurement

Each subject underwent a standard anthropometric evaluation conducted at AL/CFHD (Anthropometric Laboratory) which included, in cm, stature, sitting height, sitting eye height, sitting mid-shoulder height, sitting knee height, buttock-knee length, bideltoid breadth, right-hand thumb-tip reach, and left-hand thumb-tip reach. The four measurements of interest for the MFD task were: 1) sitting height, 2) sitting mid-shoulder height, 3) bideltoid breadth, and 4) right-hand thumb-tip reach (subjects only used the right hand during the MFD task regardless of their dominant hand; see Appendix C).

RESULTS

Choice Reaction Time Task

Reaction Time (RT)

In order to investigate the changes in RT performance between normal 1 g baseline and the five different trials at +2gz, the difference between the RTs in msec were calculated (+2gz RTs minus baseline RTs). Thus, a msec value greater than zero meant that RTs obtained during the +2gz exposure were slower than at baseline. Conversely, a msec value less than zero meant that RTs obtained during the +2gz exposure were faster than at baseline. The data were then separately analyzed by trial number (trials 1 to 5) via a simple two-tailed t-test statistic in order to see if the "difference" scores in msec were significantly greater or less than zero. As can be seen in Figure 9, RTs were significantly different from zero during trial 1 ($t=-3.996$, $p < 0.0052$) and trial 2 ($t=-4.177$, $p < 0.0042$) of the +2gz exposure. For trial 1, RTs were approximately 23 msec faster during +2gz exposure than during baseline. For trial 2, RTs were approximately 34 msec faster during +2gz exposure than during baseline.

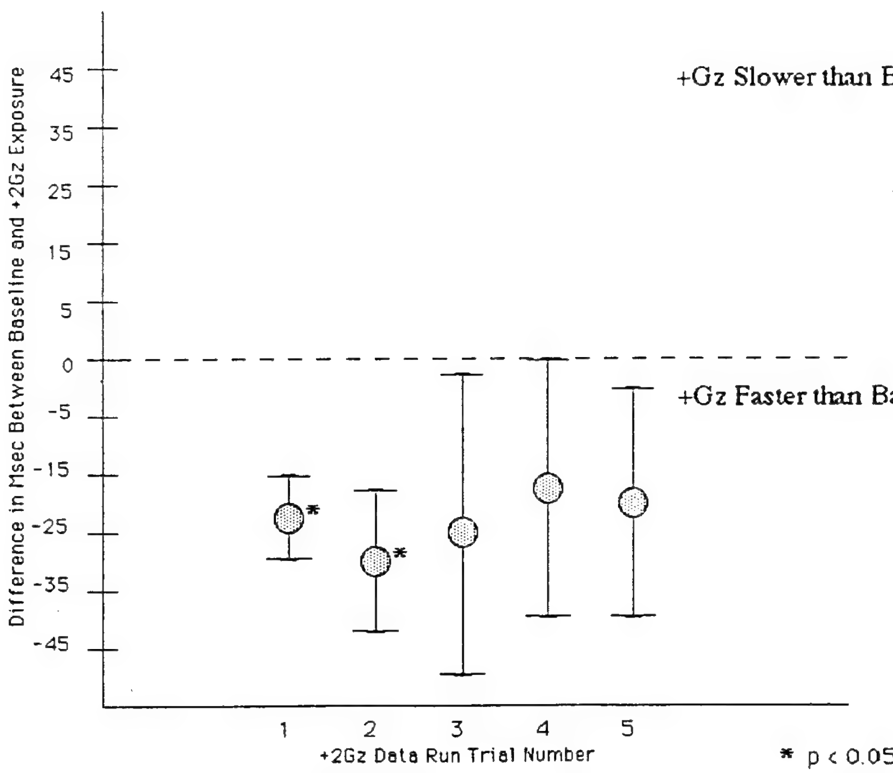


FIGURE 9. Choice Reaction Time RTs - difference between baseline and +2gz exposure.

Number of Errors

Again, the difference in number of errors between baseline and the five trials at +2gz was calculated. However, as can be seen in Figure 10, there were no significant differences between baseline and the +2gz exposure.

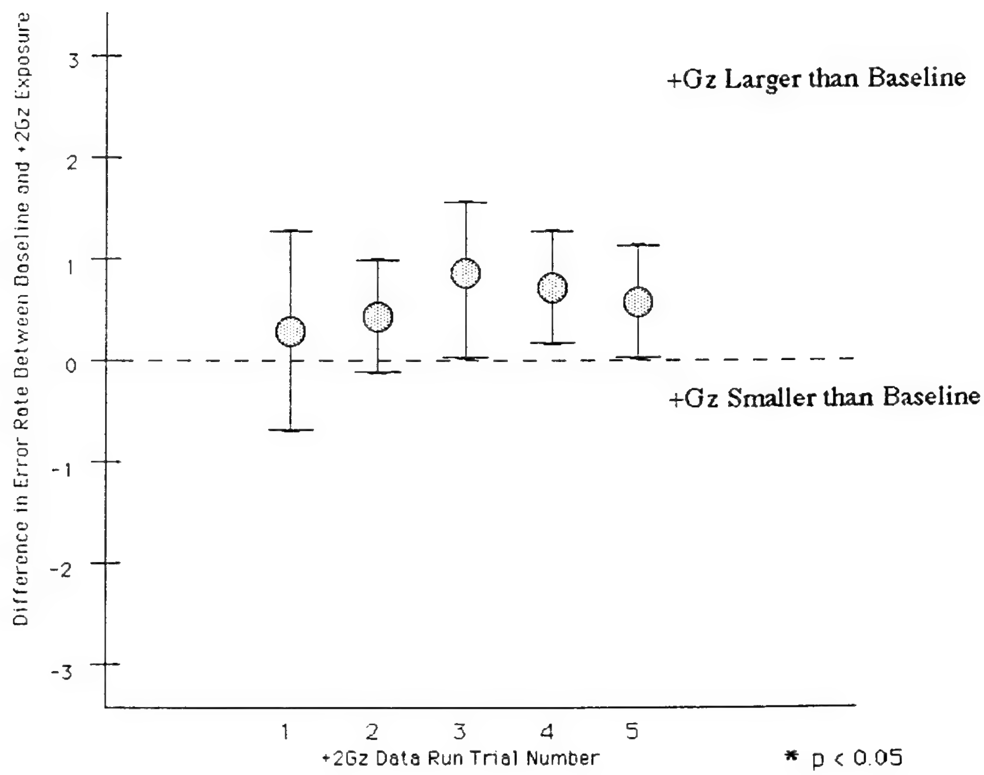


FIGURE 10. Choice Reaction Time Number of Errors - difference between baseline and +2gz exposure.

Keypad Entry Task

Reaction Time (RT)

Once again the difference in RT between baseline and the five trials during +2gz exposure was calculated. As can be seen in Figure 11, RTs were significantly different from zero for trial 1 ($t=13.347$, $p < 0.0001$), trial 2 ($t=3.047$, $p < 0.0187$), and trial 3 ($t=2.578$, $p < 0.0366$). For trial 1, RTs were approximately 422 msec slower during +2gz exposure than during baseline. For trial 2, RTs were approximately 217 msec slower during +2gz exposure than during baseline. And for trial 3, RTs were approximately 179 msec slower at +2gz exposure than during baseline.

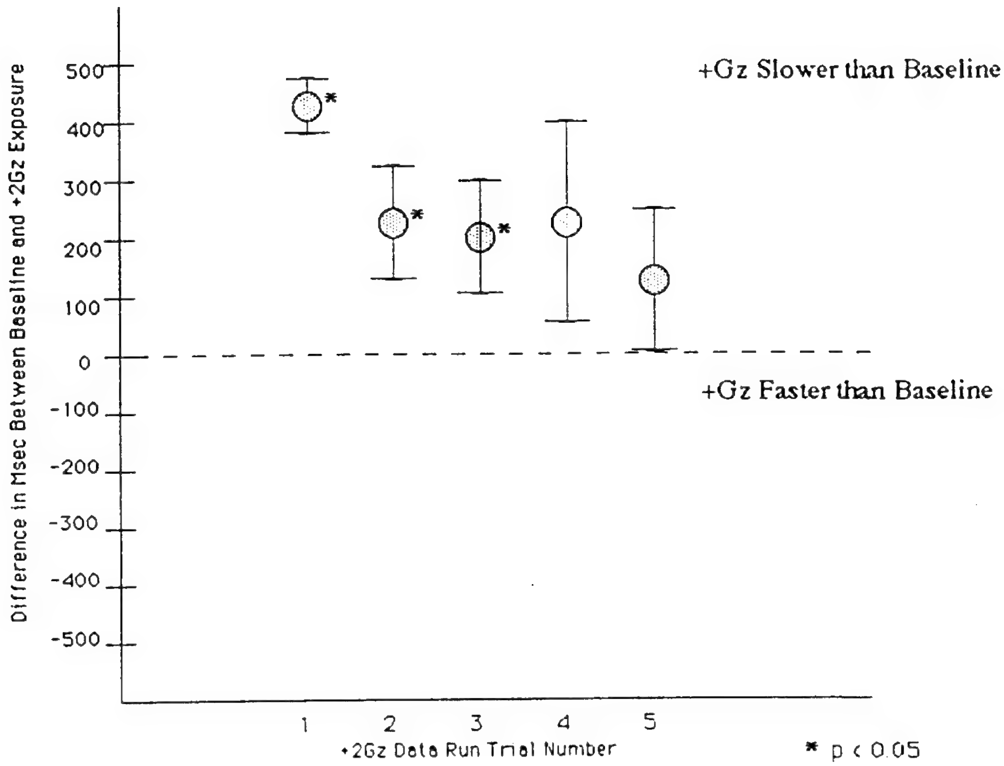


FIGURE 11. Keypad Entry Task RTs - difference between baseline and +2gz exposure.

Number of Errors

Again, the difference between baseline and the +2gz exposure was calculated. Figure 12 shows that the difference between the two was significantly different from zero for trial 1 ($t=3.103$, $p < 0.0199$), trial 4 ($t=2.525$, $p < 0.0395$) and trial 5 ($t=2.918$, $p < 0.0224$). For trial 1, the number of errors increased by approximately 1.87 during the +2gz exposure when compared to baseline. For trial 4, the number of errors increased by approximately 0.75 during the +2gz exposure when compared to baseline. And for trial 5, the number of errors increased by approximately 1.50 during the +2gz exposure when compared to baseline.

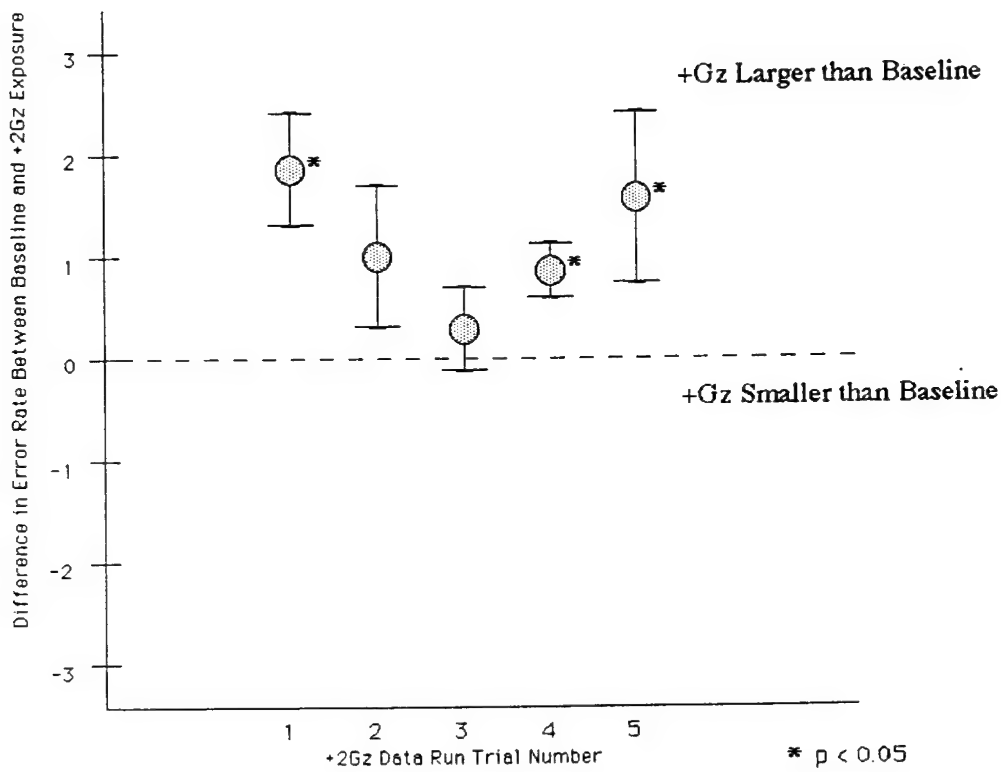


FIGURE 12. Keypad Entry Task Number of Errors - difference between baseline and +2gz exposure.

Multi-Function Display (MFD) Task

Reaction Time (RT)

The first analysis conducted on the RTs obtained from the MFD task was an ANOVA concerning the interaction between MFD button (1 to 5) and +2gz exposure trial number (1 to 5). There was no significant interaction between the two variables, but there was a significant main effect of MFD button number, $F(4,7)=15.61$, $p < 0.0001$. According to Waller-Duncan t-tests, RTs obtained from buttons 4 and 1 were longer than buttons 3 and 2, which in turn were longer than button 5. Means in msec were as follows: button 4=1131.40; button 1=1019.88; button 3=880.38; button 2=878.35; and button 5=648.18.

The next analysis concerned taking the difference between RTs obtained from baseline and RTs obtained from each of the five trials obtained during +2gz exposure, as was done for the choice reaction time and keypad entry tasks presented above. This was done separately for each MFD button.

Figure 13 shows the results for MFD button 1, were it can be seen that the difference scores were significantly different from zero for trial 1 ($t=4.848$, $p < 0.0019$) and trial 2 ($t=3.718$, $p < 0.0075$). For trial 1, RTs were approximately 300 msec slower during +2gz exposure than during baseline. For trial 2, RTs were approximately 230 msec slower during +2gz exposure than during baseline.

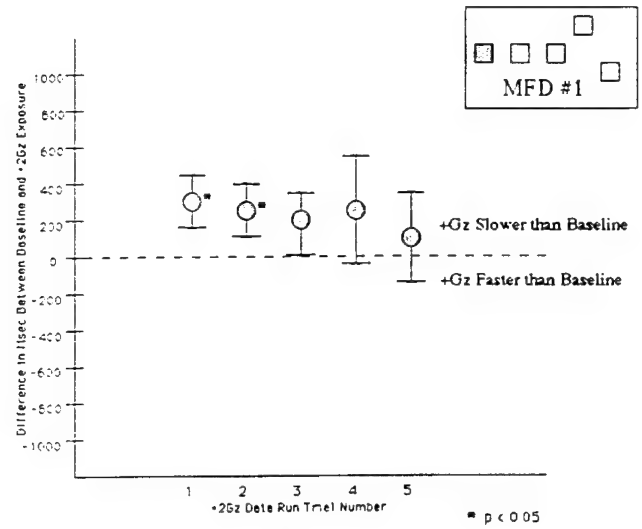


FIGURE 13. Reaction Times for MFD Button #1 - difference between baseline and +2gz exposure.

Figures 14 and 15 show the results for MFD buttons 2 and 3, respectively. As can be seen, the differences between RTs during +2gz exposure and baseline were not significantly different.

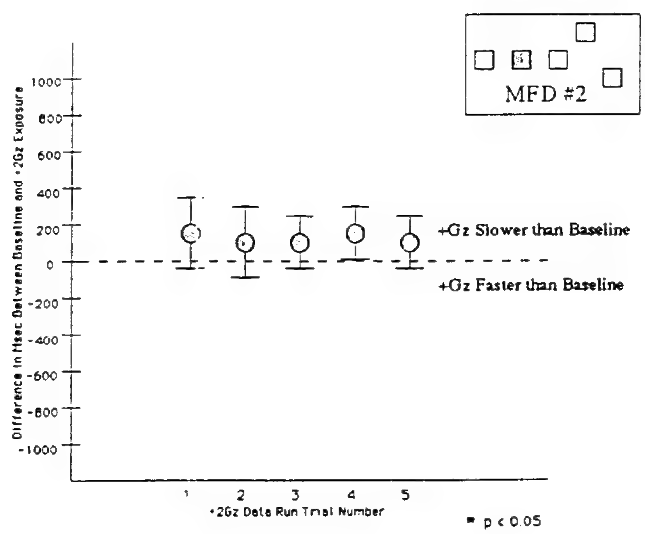


FIGURE 14. Reaction Times for MFD Button #2 - difference between baseline and +2gz exposure.

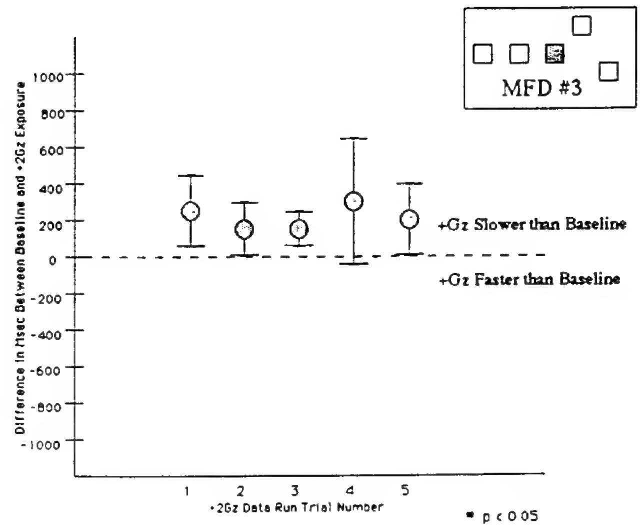


FIGURE 15. Reaction Times for MFD Button #3 - difference between baseline and +2gz exposure.

For MFD button 4, Figure 16 shows that the difference scores were statistically significant for trial 1 ($t=3.042$, $p < 0.0188$). For trial 1, RTs during the +2gz exposure were approximately 512 msec greater than at baseline.

Figure 17 shows the results for MFD button 5. As can be seen, there were no significant differences for any of the trial numbers.

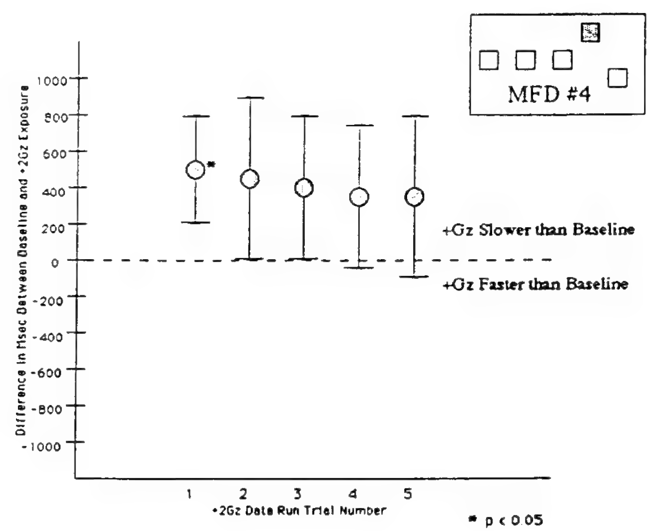


FIGURE 16. Reaction Times for MFD Button #4 - difference between baseline and +2gz exposure.

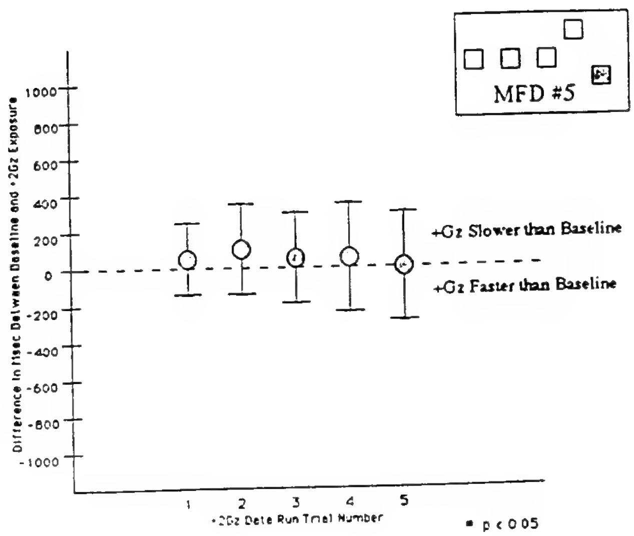


FIGURE 17. Reaction Times for MFD Button #5 - difference between baseline and +2gz exposure.

Correlations Between RT and Anthropometric Body Measurements

There were no significant correlations between RTs on the MFD task and any of the four anthropometric measurements mentioned earlier (sitting height, sitting mid-shoulder height, bideltoid breadth, or right-hand thumb-tip reach).

Three-Dimensional (3-d) Movement Data

Data from four subjects were free from electrical contamination (see Methods Section, above); thus the following statistical results were performed only with the data obtained from those four subjects. Data were separately obtained in three body axes: x, y, and z. The data were then "normalized" for the +2gz exposure by making the baseline data in all three axes the reference "zero." The area above or below the baseline zero point was then calculated for each of the four subjects by axes (x, y, and z), MFD button number (1 to 5), and trial number (1 to 5). The normalized data are shown in plot form in Appendices B1, B2, and B3 for the x, y, and z axes, respectively. These area values were then used in the statistical analyses reported below.

X-axis Area Data. There was no significant overall effect for trial number. However, according to Wilcoxon rank-sum scores, there was a significant effect for MFD button number ($p < 0.0051$). The area in the x-axis was larger for buttons 1 and 2 than for buttons 3, 4, and 5. The area means were as follows: button 1=-8.577; button 2=-5.394; button 3=-4.564; button 4=-2.622; and button 5=-2.115.

Y-axis Area Data. There was no significant effect for trial number. There was, however, a significant effect for MFD button number ($p < 0.0004$). The area in the y-axis was larger for button 4 than for buttons 1, 2, or 3, which in turn was larger than button 5. The area means are as follows: button 4=7.103; button 1=4.164; button 2, 3.733; button 3=3.258; and button 5=1.608.

Z-axis Area Data. There was a significant effect for trial number ($p < 0.0392$). The area in the z-axis was larger for trial 1 than for trials 3, 2, and 4, which in turn were larger than trial 5. The area means for trial are as follows: trial 1=5.181; trial 3=2.292; trial 2=1.795; trial 4=1.767; and trial 5=-0.595. There was also a significant effect for MFD button number ($p < 0.0001$). The area in the z-axis was larger for button 4 than for buttons 1, 3, and 2, which in turn were larger than button 5. The area means for MFD button are as follows: button 4=8.766; button 1=1.663; button 3=1.291; button 2=1.269; and button 5=-2.548.

Correlations Between 3-D Movement Area Data and Anthropometric Body Measurements

With an N size of only four, it is known that the statistical assumptions behind performing a regression equation are violated using this data set. However, as an exploratory measure, and to suggest direction of further study, the regression equations were performed nonetheless.

X-Axis. The only significant correlation between x-axis area and body measurements occurred for MFD button 1 (Figure 18). Area negatively correlated with sitting mid-shoulder height ($R^2=0.917$; $p < 0.0424$).

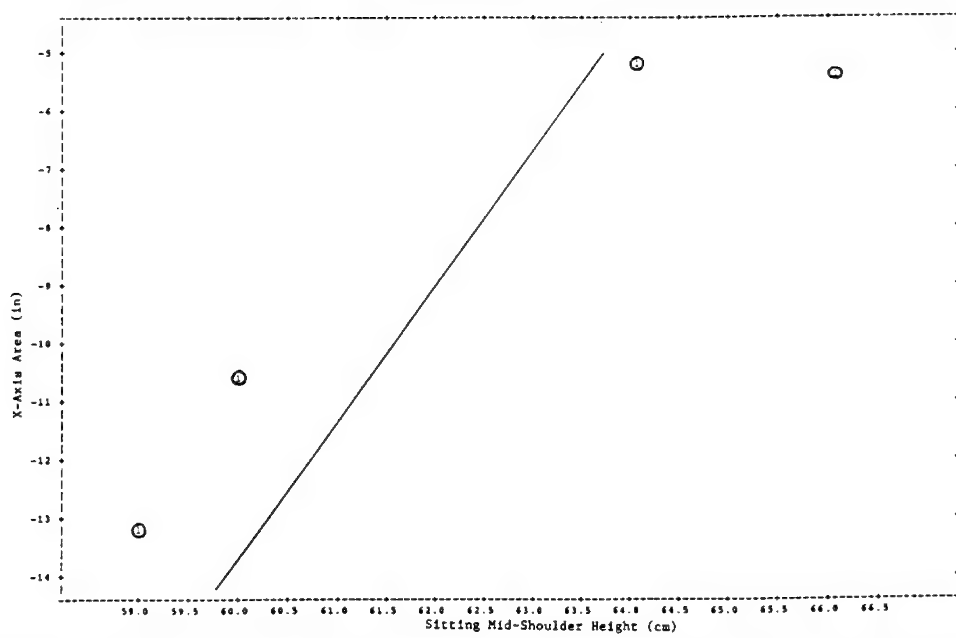


FIGURE 18. X-Axis Area Regressed With Sitting Mid-Shoulder Height - Button 1. Area=-77.898 + 1.11(Mid-Shoulder Height).

Y-Axis. The only significant correlation between y-axis area and body measurements occurred for MFD button 1 (Figure 19). Area negatively correlated with sitting mid-shoulder height ($R^2=0.8464$; $p < 0.0498$).

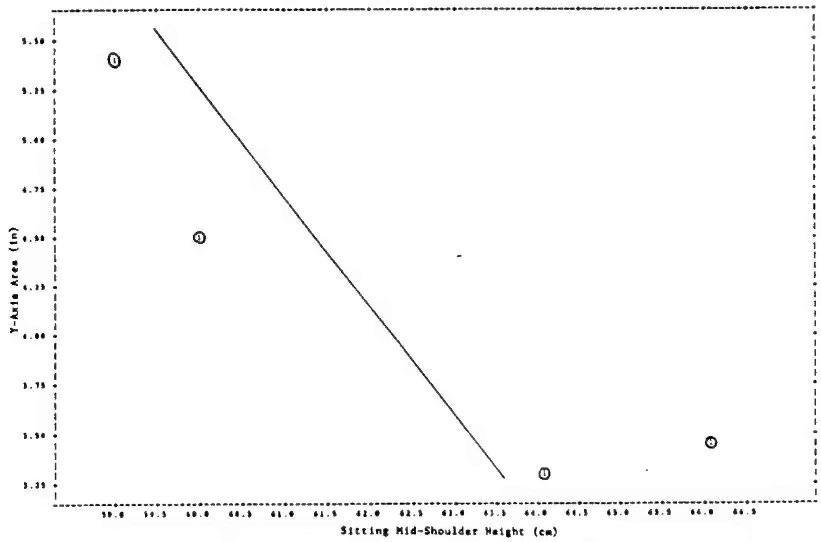


FIGURE 19. Y-Axis Area Regressed With Sitting Mid-Shoulder Height - Button 1. Area=21.005 + -0.27(Mid-Shoulder Height).

Z-Axis. The only significant correlation between z-axis area and body measurements occurred for MFD button 4 (Figure 20). Area negatively correlated with right-hand thumb-tip reach ($R^2=0.8544$; $p < 0.0538$).

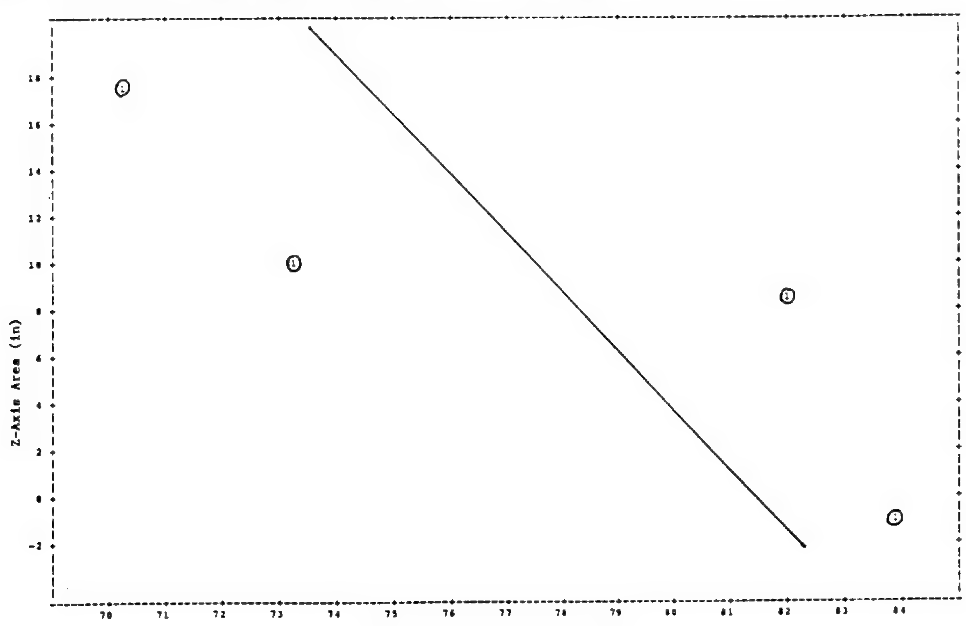


FIGURE 20. Z-Axis Area Regressed With Right-Hand Thumb-Tip Reach - Button 4. Area=68.409 + -1.26(Right Thumb-Tip Reach).

Subjective Reports

Each subject's individual responses, design recommendations, and anthropometric measurements are shown in Appendix C. The following results were obtained by averaging the number of times responses were given across the eight subjects. In many cases, responses/ recommendations total more than the number of subjects due to the fact that each subject sometimes gave more than one response.

Body Awareness

Table 2 shows the location and incidence of body pain during the +2gz exposure. As can be seen, pain in the back (lower lumbar and shoulder blade areas) was reported the most often, followed by wrist, forarm and shoulder areas, head, neck, and buttocks. All of the 8 subjects reported at least one incidence of body pain.

TABLE 2. Location and Incidence of Body Pain.

LOCATION	INCIDENCE*	REASONS GIVEN
Back (lower lumbar and between shoulder blades)	7	- wrong seat back angle - no lumbar support - reaching forward during MFD task - wrong harness fit
Wrist/Forearm/Shoulder	3	- no arm supports during keypad task - wrong angle of keypad - increased weight of arm/hand during MFD task
Head	3	- pain at top of head due to increased weight of helmet - absence of helmet liner
Neck	1	- head tilted downward during keypad task
Buttocks	1	- lack of adequate seat cushion
None	0	n/a

* Incidence may average more than the number of subjects. Some subjects gave more than one type of report.

Table 3 shows the location and incidence of body fatigue. These reports mimic the reports of body pain. Wrist, forearm, and shoulder fatigue was the most common, followed by the neck and back areas. Two of the 8 subjects reported no incidence of fatigue in any body area.

TABLE 3. Location and Incidence of Body Fatigue.

LOCATION	INCIDENCE*	REASONS GIVEN
Wrist/Forearm/Shoulder	6	- wrong arm angle for keypad task - lack of arm supports during keypad task - overall increased g and task requirements
Neck	3	- heaviness of head and helmet - overall increased g and task requirements
Lower/Middle Back	2	- reach/leaning forward during MFD task - wrong harness fit
None	2	n/a

* Incidence may average more than the number of subjects. Some subjects gave more than one type of report.

Table 4 shows the location and incidence of a noticeable increase in weight of body parts. An increase in weight of the arms and hands was the most reported, followed by the head, loss of arm/hand control, and an increase in the weight of the whole body. All of the 8 subjects reported a perceived increase in weight of at least one part of the body.

TABLE 4. Noticeable Increase in Weight of Body Parts.

LOCATION	INCIDENCE*	REASONS GIVEN
Arms/Hands	8	- reach during MFD task - movement of fingers and wrist during keypad task
Head	5	- increased head and helmet weight during +2gz
Loss of Arm/Hand Control	4	- reach during MFD task
Whole Body	2	- more effort required to move whole body into desired position during +2gz
None	0	n/a

* Incidence may average more than the number of subjects. Some subjects gave more than one type of report.

Table 5 shows the type and incidence of disorientation subjects reported. Dizziness and/or a tumbling sensation occurred during acceleration/deceleration of the centrifuge, or when subjects were leaning forward to reach MFD buttons during the task. Lightheadedness accompanied by a feeling of falling/floating occurred after the centrifuge had come to a stop for 2 subjects. There was 1 report of stomach discomfort during the keypad task. One subject reported no symptoms at all.

TABLE 5. Type and Incidence of Disorientation.

TYPE	INCIDENCE*	REASONS GIVEN
Dizziness and/or Tumbling Sensation	5	- acceleration/deceleration of the centrifuge - twisting and leaning forward during MFD task
Lightheadedness with Feeling of Falling or Floating	2	- readaptation to 1g after prolonged exposure to +2gz
Stomach Discomfort	1	- moving eyes up and down while holding head steady during keypad task
None	1	n/a

* Incidence may average more than the number of subjects. Some subjects gave more than one type of report.

Design Recommendations

Table 6 shows the recommendations for the seat design. The addition of a lumbar support was recommended the most, followed by a seat back which could be adjusted by each subject. Adding cushions, or extending the cushions to other areas of the seat, were recommended 5 times. Only 1 subject gave no recommendations to improve the seat design.

TABLE 6. Recommendations for Seat Design.

TYPE	INCIDENCE*
Lumbar Support	6
Adjustable Seat Back Angle	5
Cushion on Seat Pan	2
Cushion Over Entire Seat Surface	2
30° Seat Back Angle	1
Extension of Padded Seat to Sides of Knees/Legs	1
None	1

* Incidence may average more than the number of subjects. Some subjects gave more than one type of report.

Table 7 shows the design recommendations for the choice reaction time task. Of all 3 tasks, this task had the least amount of suggestions to improve the design. There were 2 suggestions to move the response pad up to the plane of the knees, and 1 suggestion to increase the resistance of the buttons.

TABLE 7. Recommendations for Choice Reaction Time Task Design.

TYPE	INCIDENCE*
None	6
Move Response Pad Up Towards Top of Knees	2
Make Buttons Harder to Push (increase resistance)	1

* Incidence may average more than the number of subjects. Some subjects gave more than one type of report.

Table 8 shows the recommendations for the keypad task. A response pad which would provide an adjustable angle, and the addition of an arm support were the most highly recommended changes for this task. There were 2 recommendations to mount the keypad in the line of sight of the visual display, and another 2 recommendations to move the keypad from between the knees to the left side of the seat. The majority of the remaining recommendations centered on the keypad itself, such as increasing the size of the buttons, spacing them farther apart, and decreasing their resistance. All 8 subjects had at least one recommendation to improve the keypad task.

TABLE 8. Recommendations for Keypad Task Design.

TYPE	INCIDENCE*
Provide Adjustable Angle for Response Pad	4
Add Arm Supports	3
Mount in Line of Sight	2
Move From Between Knees to Left Side of Seat	2
Provide More Space Between Buttons	2
Make Buttons Larger	1
Make Buttons Easier to Push	1
Lower Keypad to Rest Arms on Thighs	1
Move Closer to Body	1
None	0

* Incidence may average more than the number of subjects. Some subjects gave more than one type of report.

Table 9 shows the recommendations for the MFD task. The one recommendation that every subject gave was to move the top MFD down, or to remove it altogether. Moving the left-most MFD toward the middle was recommended 4 times. There were 2 recommendations to move the entire MFD mount closer to the seat (and hence to the subject), and 2 recommendations to add more buttons on the MFDs to improve realism. All 8 subjects had at least one recommendation to improve the design of the MFD task.

TABLE 9. Recommendations for MFD Reach Task Design.

TYPE	INCIDENCE*
Move Top-Most MFD Down, or Remove	8
Move Left-Most MFD to Middle	4
Move All MFDs Closer to Seat	2
Add More Buttons on MFDs to Improve Realism	2
Move Lower Right MFD to Left	1
Don't Put Something Important Between MFDs and Stick/Throttle	1
None	0

* Incidence may average more than the number of subjects. Some subjects gave more than one type of report.

Table 10 shows the recommendations for the stick, throttle, and rudder design. Five of the subjects had no recommendations to improve the design. There were 2 suggestions to move the right arm rest and flight stick closer to the seat, 1 recommendation to move the stick and throttles away from the sides of the knees (up and in towards the subject), and 1 recommendation to add a left-hand arm rest for the throttle.

TABLE 10. Recommendations for Stick, Throttle, or Rudder Design.

TYPE	INCIDENCE*
None	5
Move Arm Rest and Flight Stick Closer to Seat	2
Move Stick and Throttle Away from Sides of Knees (up and in)	1
Throttle Needs Arm Rest	1

* Incidence may average more than the number of subjects. Some subjects gave more than one type of report.

Results Summary

Fine Motor Control Tasks: Choice Reaction Time and Keypad Entry

For the choice reaction time task, RTs were faster under +2gz for trials 1 and 2 than at baseline, while number of errors showed no differences. Conversely, for the keypad entry task, RTs were slower under +2gz for trials 1, 2, and 3 than at baseline, while number of errors increased during trials 1, 4, and 5 of the +2gz exposure.

Gross Motor Control Task: Multi-Function Display (MFD)

Overall, RTs were slower for MFD buttons 4 and 1 than for buttons 3 and 2, which in turn were slower than button 5. For MFD button 1, trials 1 and 2 during +2gz exposure had RTs slower than during baseline. For MFD button 4, trial 1 during +2gz exposure had slower RTs than during baseline.

For the 3-d movement data, area in the x-axis was larger for MFD buttons 1 and 2 than for buttons 3, 4, and 5. Area in the y-axis was larger for button 4 than for buttons 1, 2, and 3, which in turn were larger than button 5. For the z-axis data, area was larger during trial 1 than trial 3, 2, and 4, which in turn were larger than trial 5. Z-axis area was also larger for MFD button 4 than for buttons 1, 3, and 2, which in turn were larger than button 5.

Correlations with the anthropometric data showed that, for MFD button 1 in both the x-axis and y-axis, as sitting mid-shoulder height increased, movement area decreased. For MFD button 4 in the z-axis, as right-hand thumb-tip reach increased, movement area decreased.

Subjective Reports and Design Recommendations

Overall, subjects reported body awareness (pain, fatigue, and increased weight of body parts) to be a function of the seat back angle of the seat, as well as the design of the tasks. Specifically, subjects recommended an adjustable seat back angle, the addition of a lumbar support, and extra seat padding in response to the incidence of back and shoulder pain during the long-term exposure to +2gz. In addition, subjects recommended that the keypad entry response mount be adjustable to reduce finger, wrist, and forearm fatigue due to extreme and uncomfortable hand/wrist angles during performance of the task. Subjects also recommended that the top-most MFD be lowered or removed and the left-most MFD be brought in towards the middle to reduce the amount of reaching, and hence shoulder and back discomfort they experienced.

DISCUSSION

Research Results

The choice reaction time task did not show the expected decrease in performance during exposure to the +2gz profile; in fact, subjects increased their performance levels during the first two sessions under acceleration. This suggests an inverted-U phenomenon as discussed in the Introduction. It may be that this task was so easy to perform that subjects were not giving their best effort at 1g, while the added stress of the increased g-level increased subjects' "arousal" level to the point where improved performance occurred. These results further suggest that this task is a poor candidate for low-level acceleration research, which directly contradicts earlier research reports concerning the performance stability of such tasks during higher g levels. This contradiction may be a result of the amount of training subjects in this experiment experienced, and/or the differences in g level. It may be that the task was so automatic that even the added perceived weight of the fingers, hands, and arms were easily overcome by extra effort, which in turn provided increased performance levels above those found at 1g. However, the pattern of results also suggest that subjects reduced the level of extra effort after the first two sessions under +2gz, where they returned to baseline levels of performance. This could be attributed to adaptation to the situation, a slight relaxation of exertion levels, fatigue, or a conscious "calibration" of performance effort.

The keypad entry task showed an increase in both RT and errors during the first session under +2gz. This suggests that the initial exposure to increased g caused the performance decrement. In addition, RT was also increased over 1g baseline during sessions 2 and 3, while error rate was not. This may be attributed to a speed-accuracy tradeoff by the subjects (subjects slowed their RTs in order to decrease the number of errors). However, RTs returned to 1g baseline levels during the last two sessions under +2gz, while errors increased. Again, subjects may have adjusted their speed-accuracy tradeoff by increasing their RTs without worrying about errors due to fatigue. On the other hand if RTs and errors are considered separately, a case could be made that the RTs showed an adaptation effect (performance decrement at the beginning of the +2gz exposure which improved with time), while the errors showed an inverted-U phenomenon. Errors may have increased at the start due to over-arousal, whereupon subjects adjusted their performance levels during the second and third sessions at which time errors decreased. Then during the last two sessions this "adjustment" could not be maintained and errors once again increased over 1g levels.

As expected, RTs for the top-most and left-most MFDs were greater than for the middle and right-most MFDs. In addition, RTs for the top-most and left-most MFDs showed a performance decrement due to increased g, which the other MFDs did not. For the top-most MFD, RTs were slower during the first +2gz session than at 1g, while the later sessions showed no such effect. This suggests that subjects "recalibrated" their gross arm movements to compensate for the increased g. The 3-d

data in the z-axis support this recalibration theory for the top-most MFD, where movement area (overshoot/undershoot) was larger during the first session than during the second, third, and fourth session, which in turn was larger than the fifth session. For the left-most MFDs, performance decrements were found for the first two sessions. Again, this suggests a recalibration effect of gross motor movement.

The 3-d movement data were difficult to interpret in that the x and y axes were switched in relation to the true body axes (see Appendix B). However, the regression equations obtained for *both* the x and y axes suggests that movement area decreased as sitting mid-shoulder height increased for the left-most MFD. In addition, the regression equation obtained for the z-axis suggests that movement area decreased as right thumb-tip reach increased for the top-most MFD. The left-most and top-most MFDs represented the two extreme positions of all the MFDs, and if anthropometric differences between the subjects were to have an impact on gross motor movement performance, these two MFDs would be the place to look. Basically, the taller the shoulder while sitting in the seat, and the longer the arm length to the end of the hand, the less error subjects made in the movement path to reach the two extreme MFDs. It should be remembered, however, that these results were based on data from only 4 subjects. Nevertheless, these results suggest that this type of 3-d measurement, coupled with individual anthropometric measurement, should be used in future high-g motor movement research.

Location and incidence of body pain and fatigue during the +2gz exposure were mostly due to problems with the design of the seat, the keypad entry task, and the MFD task. To alleviate these problems, subjects recommended the following design changes: 1) provide a seat with an adjustable seat back angle, lumbar support, and padding over the entire seat area; 2) provide a keypad entry device with an adjustable angle coupled with an arm support, and larger buttons spaced farther apart; and 2) lower or remove the top-most MFD, and bring in towards the middle or remove the left-most MFD.

Disorientation which occurred during the +2gz exposure for 5 subjects was mostly due to the basic limitations of a short-arm centrifuge, mainly, the angular displacement geometry of acceleration/deceleration which causes unnatural stimulation of the semi-circular canals within the inner ear. Also, 3 subjects reported a limited coriolis effect due to up and down eye/head movements required for the keypad task, and twisting/leaning forward for the MFD task during rotation of the centrifuge. These are side-effects of centrifuge simulation and should not impact NASP design issues. However, 2 subjects reported effects not related to acceleration/deceleration or coriolis; both reported feelings of lightheadedness with a feeling of falling/floating for a short period when they returned to normal 1g. This suggests a possible adverse effect related to the otoliths of the inner ear which cannot be explained away as a simulation artifact, and should be addressed via future research into adaptation effects for use in NASP crewsystems design.

Design Recommendations

According to the results of this study, an ideal seat design for use in long-term low-level acceleration environments would include three additions: 1) an adjustable seatback angle, 2) lumbar supports, and 3) extra padding covering the entire seat area. However, it's recognized that providing an adjustable seat could change the entire anthropometric cockpit design for each subject (e.g., eye point-of-regard, arm length needed for forward mounted controls, etc.). Adjustable seat back angles and lumbar supports could also cause safety problems with emergency ejection sequences. In addition, lumbar supports and extra seat padding could, instead of providing a damping effect, cause more vibration energy to pass to the pilot's body. The cost-to-benefit ratios of providing or not providing the above three additions would need to be identified through further concept design studies, and in some cases may require seat design "fly offs."

The keypad entry device used in this study was a standard telephone keypad with 1/2" by 1/2" square buttons, each separated by 1/4" (see Appendix A2). Keypad entry devices should have buttons at least 3/4 inch by 3/4 inch in order to reduce the errors encountered in this study. The ideal keypad entry device for use during long-term low-level acceleration would include a swivel mount which could be positioned for a comfortable wrist angle, along with a fold-away arm rest. The design suggestions for button size and swivel mount should pose no special problems, but the arm rest could affect the safety of ejection sequences if it projects into the ejection envelope. Again, concept study designs need to be completed to address this design tradeoff.

Any input device which requires large arm/hand movements will probably cause greater motion error when positioned at horizontal and vertical extremes. The left-most MFD caused increased movement error due to the need to horizontally reach across the body 29" from the position of the flight stick (Appendix A3). The top-most MFD caused increased movement error due to the need to vertically reach 12 more inches than the other displays (Appendix A4). The ideal MFDs should be mounted no farther than 21 inches from the floor and 35 inches away from the intersection of the seat back/pan of an ACES II-type seat. These design maximums may of course change with a different seat/stick cockpit design, but they should not change by much.

Directions for Future Research

Any aircraft design which has long-term low-level acceleration profiles as part of its mission scenario needs to address the issues of crewmember performance and comfort. This research effort has identified areas of which cockpit designers need to be cognizant, namely, reach errors under acceleration as low as +2gz, keypad entry performance decrements due to poor keypad design (the device itself, as well as how it's mounted), reduced comfort/increased incidence of pain due to poor seat design, and possible adaptation effects that may affect spatial orientation upon returning to normal 1g.

We've attempted to provide a few guidelines for use in this type of cockpit design. However, as in any design effort, tradeoffs need to be made among almost an infinite number of variables. We recommend that before choosing a final design, ground-based centrifuge testing should be conducted. The capability is now in place to provide a valid methodology for determining which design of many is best in terms of crewmember performance and comfort.

In addition, this study showed that basic anthropometric measures can be related to reach error under low-level g. Further research needs to be conducted to determine the overall validity of this finding. If the finding is replicated, this relationship could have a wide range of applications for crewmember selection. Adaptation effects for gross motor movement were also demonstrated here, and may point to the need for training crewmembers under +2-3gz profiles before actual flight tests. Training through centrifuge demonstration may provide early gross motor movement "re-calibration" -- at the very least it would provide crewmembers with an idea of what to expect. Further research needs to be done in this training area.

Finally, some crewmembers may show adaptation effects to long-term low-level acceleration that are evident only upon return to normal 1g. These effects may include the disorienting feelings of lightheadedness and/or floating or falling. This type of disorientation can obviously be dangerous for crewmembers in control of the aircraft. Future research needs to focus on this effect to determine its causes, its prevalence, and any possible design solutions.

REFERENCES

Albery, W. B., Ward, S. L., and Gill, R. T. (1985). The effect of acceleration stress on human workload. AMRL-TR-85-039. Wright-Patterson AFB, Ohio: Aerospace Medical Research Laboratory (DTIC-AD-A156770).

Braunstein and White (1962). The effects of acceleration on brightness discrimination. Journal of the Optical Society of America, 52, 931-933.

Burton, R. R., and Jaggars, J. L. (1974). Influence of ethyl alcohol ingestion on a target task during sustained +gz centrifugation. Aerospace Medicine, 45, 290-296.

Canfield, A. A., Comrey, A. L., and Wilson, R. C. (1949). The effect of increased acceleration upon human abilities, Part II: Perceptual speed ability (Report No. RR-4). Los Angeles, CA: University of Southern California.

Chambers, R. M. (1961). Control performance under acceleration with side-arm controllers. NADC-MA-6110. Johnsville, PA: Naval Air Development Center (DTIC-AD-269487).

Chambers, R. M. (1963). Operator performance in acceleration environments. In Unusual Environments and Human Behavior (N. M. Burns, R. M. Chambers, and E. Hendler, Eds.), pp. 193-319. New York: The Free Press of Glencoe.

Chambers, R. M. and Hitchcock, L., Jr. (1963). Effects of acceleration on pilot performance. NADC-MA-6330. Johnsville, PA: Naval Air Development Center (DTIC-AD-408686).

Creer, B. Y. (1962). Impedence of sustained acceleration on certain pilot performance capabilities. Aerospace Medicine, 33, 1086-1093.

Darwood, J. J., Repperger, D. W., and Goodyear, C. D. (1991). Mass discrimination under +gz acceleration. Aviation, Space, and Environmental Medicine, 62, 319-324.

Domaszuk, J., and Wojtkowiak, M. (1975). Zachowanie sie zdolnosci spostrezegania i czasu reakcji wzrokowo-ruchowej pilota podczas dzialania przyspieszen +gz (Retention of perception and pilot's motor-visual reaction time during +gz acceleration). In The 1st National Scientific-Technological Conference: Ergonomics in Aviation, pp. 73-80. Warsaw, Poland: Instytut Lotnictwa (abstract translated from Polish).

Frankenhauser, M. (1945). Effects of prolonged gravitational stress on performance. Acta Psychologica, 104, 10-11.

Fraser, T. M. (1973). Sustained linear acceleration. In Bioastronautics Data Book (J. J. Parker and V. R. West, Eds.). Washington, DC: US Government Printing Office (Stock Number 3300-00474).

Frazier, J. W., Repperger, D. W, and Popper, S. E. (1990). Time estimating ability during +gz stress. Aviation, Space, and Environmental Medicine, 61, A1.

Grether, W. F. (1971). Acceleration and human performance. Aerospace Medicine, 42, 1157-1166.

Hallenbeck, G. A. (1946). Design and use of anti-g suits and their activation valves in World War II. Report No. 5433. Wright-Patterson AFB, Oh.

Kerr, W. K. and Russell, W. A. M. (1944). Effects of positive acceleration in the centrifuge and in aircraft on functions of the nervous system. Report No. C2719. Canada: National Research Council (DTIC-AD-494706).

Little, V. Z., Hartman, B. O., and Leverett, S. D. (1968). Effects of acceleration on human performance and physiology, with special reference to transverse g. USAFSAM-4-68). Brooks AFB, TX: USAF School of Aerospace Medicine (DTIC-AD-676209).

Loose, D. R., McElreath, K. W., and Potor, G., Jr. (1976). The effects of direct side force control on pilot tracking performance. AFAMRL-TR-76-87. Wright-Patterson AFB, OH: AF Aerospace Medical Research Laboratory (DTIC-AD-A036083).

McCloskey, K. A., Tripp, L. D., Chelette, T. L., and Popper, S. E. (1992). Test and evaluation metrics for use in sustained acceleration research. Human Factors, 34, 409-428.

Piranian, A. G. (1982). Effects of sustained acceleration, airframe buffet, and aircraft flying qualities on tracking performance. In Proceedings of the Workshop on Flight Testing to Identify Pilot Workload and Pilot Dynamics, pp. 92-101. Edwards AFB, CA: American Institute of Aeronautics and Astronautics.

Popper, S. E., Repperger, D. W., McCloskey, K., and Tripp, L. D. (1992). The effects of multiple environmental stressors on human performance. In The 5th Annual Workshop on Space Operations, Applications, and Research (SOAR '92), Vol.2, pp. 487-495. Houston, TX: Johnson Space Center-NASA.

Popper, S. E., Repperger, D. W., Frazier, J. W., and Goodyear, C. (1990). Changes in time estimating abilities through workload analysis as measured by +gz acceleration. In Proceedings of the IEEE National Aerospace and Electronics Conference (NAECON '90), Vol. 2, pp. 862-868. New York: IEEE Publishing.

von Gierke, H. E., McCloskey, K., and Albery, W. B. (1991). Military performance in sustained acceleration and vibration environments. In Handbook of Military Psychology (R. Gal and A. D. Mangelsdorff, Eds.), pp. 335-364. London: Wiley & Sons.

Voge, V. M. (1980). Acceleration forces on the human subject. Aviation, Space, and Environmental Medicine, 51, 970-980.

Warrick, M. J. and Lund, D. W. (1946). Effect of moderate positive acceleration (g) on the ability to read aircraft instrument dials. Memorandum-TSEAA-694-10. Wright-Patterson AFB, OH.

White, W. J. (1958). Acceleration and vision. WADC-TR-58-533. Warminster, PA: Warminster Air Development Center (DTIC-AD-208147).

White, W. J. (1960). Variations in absolute vision thresholds during acceleration stress. ASD-TR-60-34. Wright-Patterson AFB, OH: Aerospace Systems Division (DTIC-AD-243612).

White, W. J. and Monty, R. A. (1965). Vision and unusual gravitational forces. In Visual Capabilities in the Space Environment (C. A. Baker, Ed.), pp. 65-89. New York: Pergamon Press.

Yerkes, R. M. and Dodson, J. D. (1908). The relationship of strength of stimulus to rapidity of habit-formation. Journal of Comparative Neurology and Psychology, 18, 459-482.

APPENDIX A.

A1. Dimensions of the Seat Used in the Subject Cab.

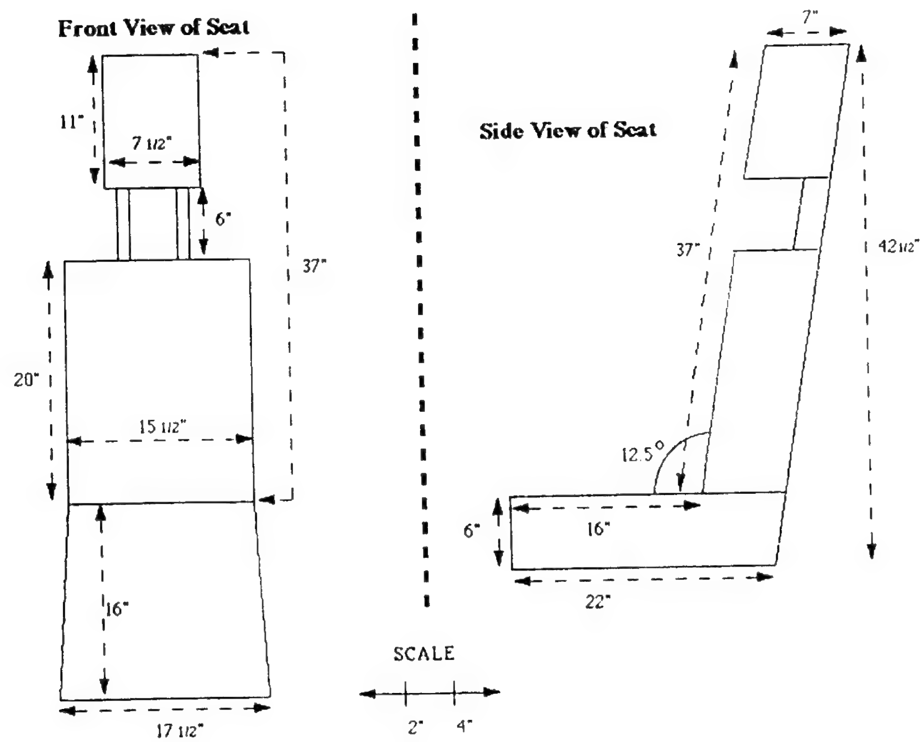
A2. Dimensions of the Keypad Entry Device and Four-Button Response Pad Console.

A3. Dimensions of the Multi-Function Display (MFD) Mounts.

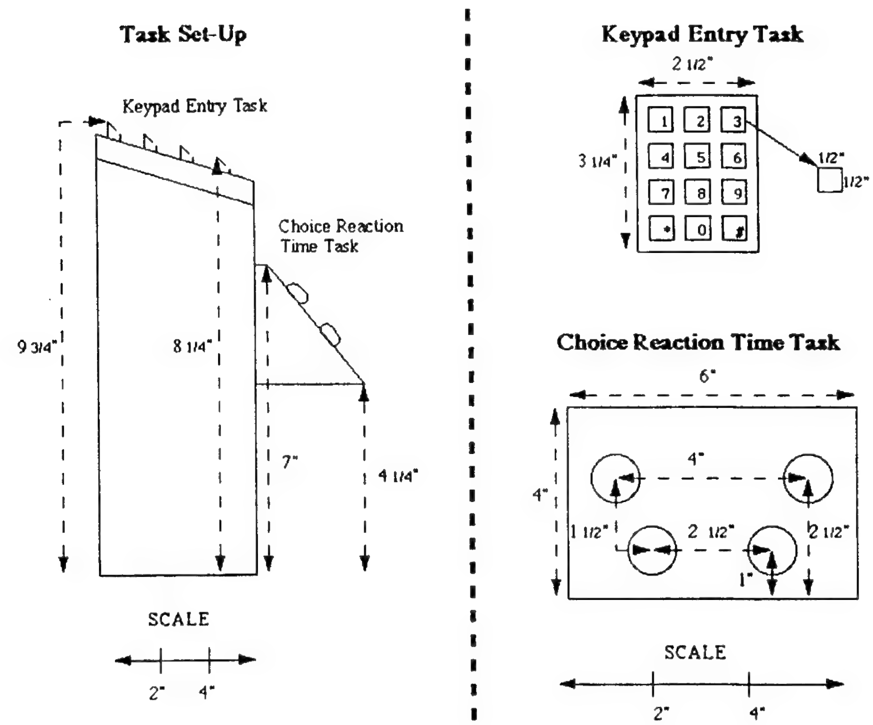
A4. Reference from the Seat to the Entry Devices.

A5. Global Dimensions of the Entire Experimental Station.

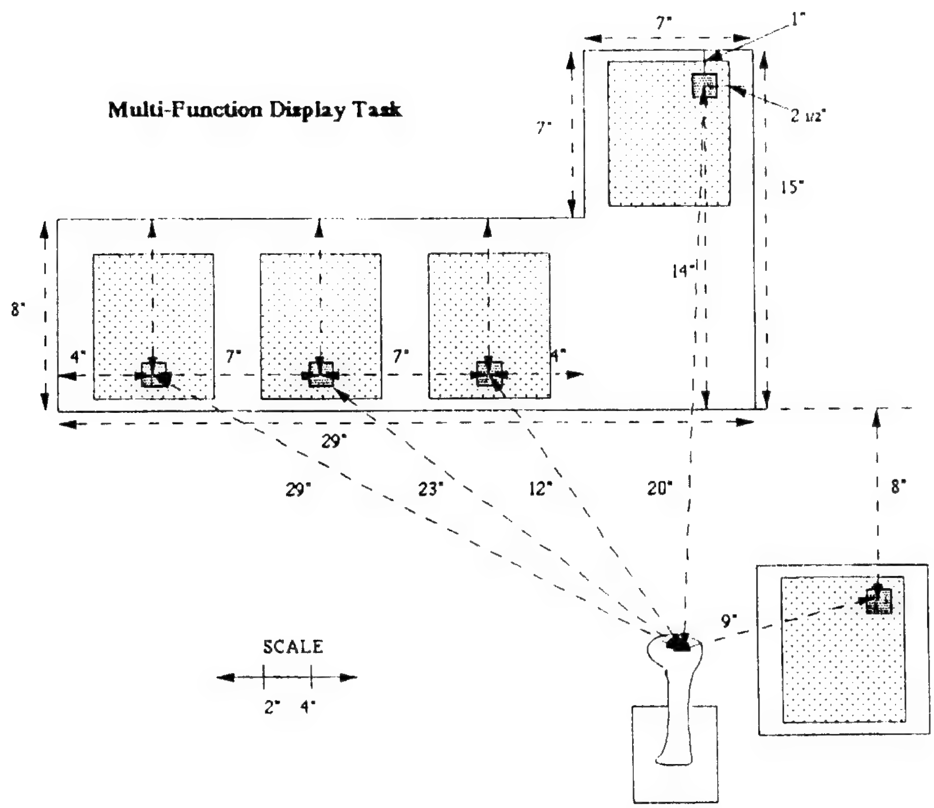
A1. Dimensions of the Seat Used in the Subject Cab.



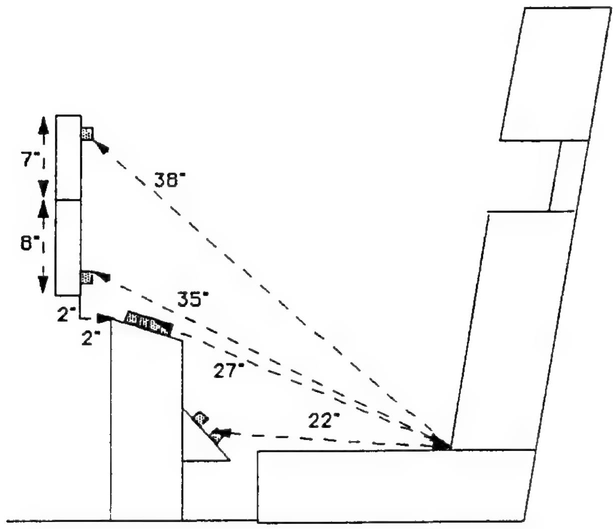
A2. Dimensions of the Keypad Entry Device and Four-Button Response Pad Console.



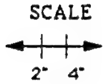
A3. Dimensions of the Multi-Function Display (MFD) Mounts.

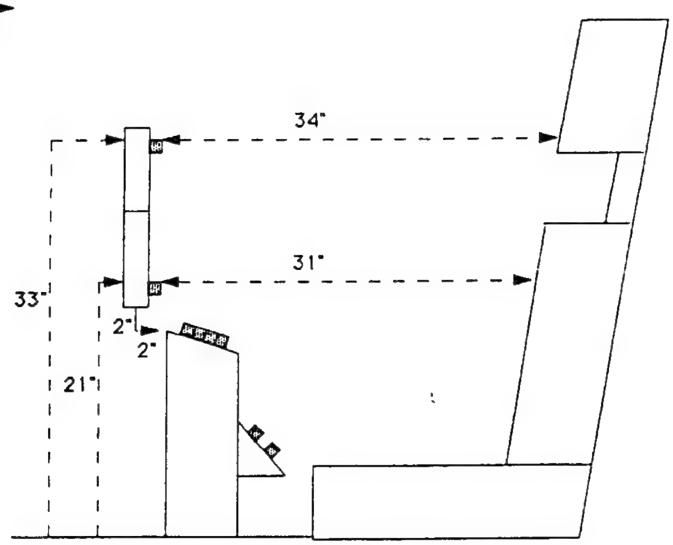


A4. Reference from the Seat to the Entry Devices.



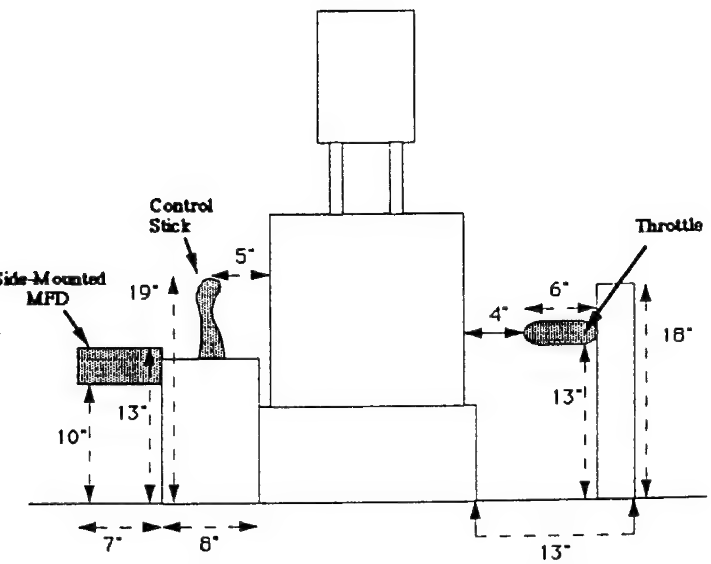
Reference from Seat Pan/Seat Back Intersection



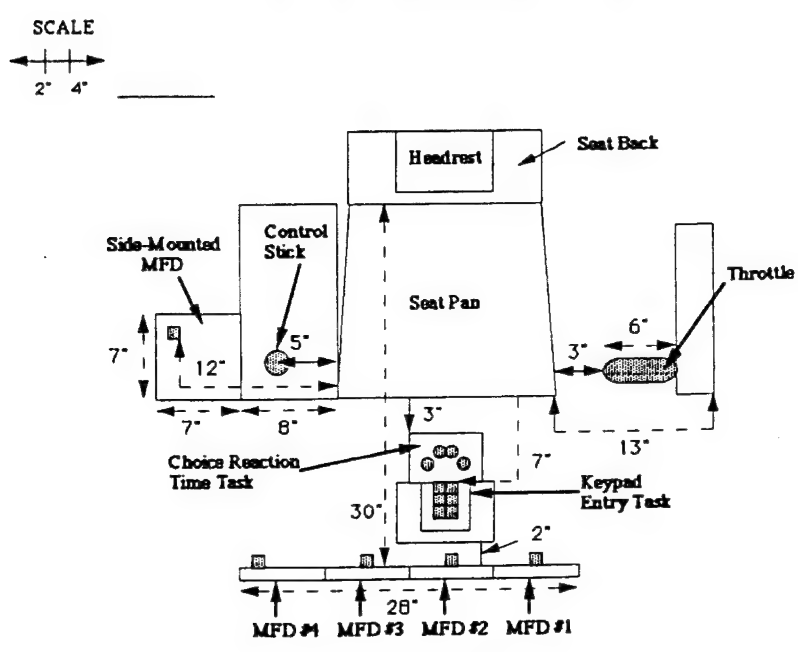


Reference from MFD Button Height

A5. Global Dimensions of the Entire Experimental Station.



Front View Without Keypads or MFDs



Top-Down View

APPENDIX B.

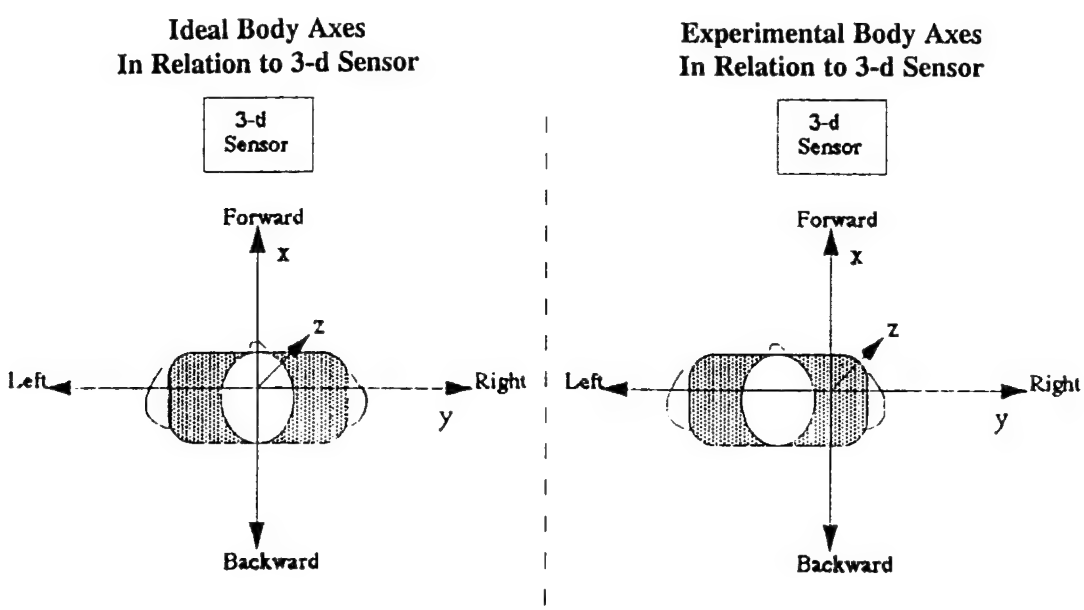
B1. X-Axis Plots of Normalized 3-d Data.

B2. Y-Axis Plots of Normalized 3-d Data.

B3. Z-Axis Plots of Normalized 3-d Data.

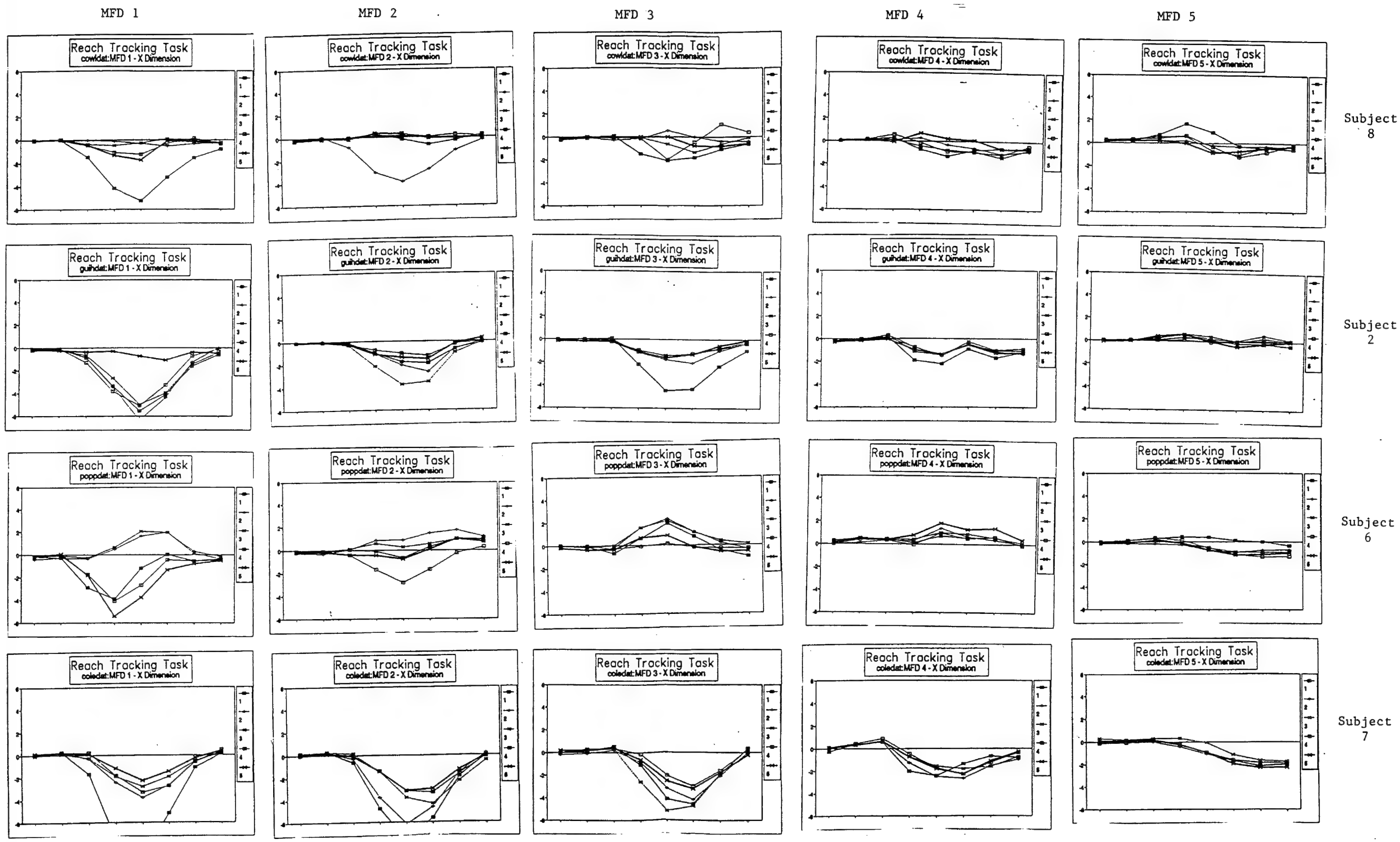
Interpreting the Plots. Each subject had a different data set length due to variations in the time it took for them to pull the trigger on the flight stick and then push the bezel button. Accordingly, each data set file was divided into eighths (1/8) from beginning to end, and an average value taken from each of the 8 "bins" (this is the reason for the 8 equal hacks along the bottom of each plot). Thus, sets of varying lengths were rendered comparable. The variable "area" was calculated by simply adding all 3-d values across the 8 bins together, regardless of positive or negative sign. In addition, the "zero" line placed horizontal within each plot is the baseline values of movement, and all excursions above and below the zero line reflects variation away from the baseline values during +2gz exposure (the units are in inches). Finally, the symbols in the vertical column at the right of each plot correspond to the trial run numbers 1, 2, 3, 4, and 5 (1 was the first trial run under +2gz, while 5 was the last).

While it would be convenient to be able to say that the x, y, and z axes reported here correspond simply in a 1-to-1 fashion with the body axes, this is not the case. The x, y, and z axes correspond to the position of The Bird™ transmitter in relation to the receiver located on the back of each subject's hand. The transmitter was located directly in front of the flight stick, mounted underneath the MFD mount. Thus, the axes corresponded to the graphic, below.

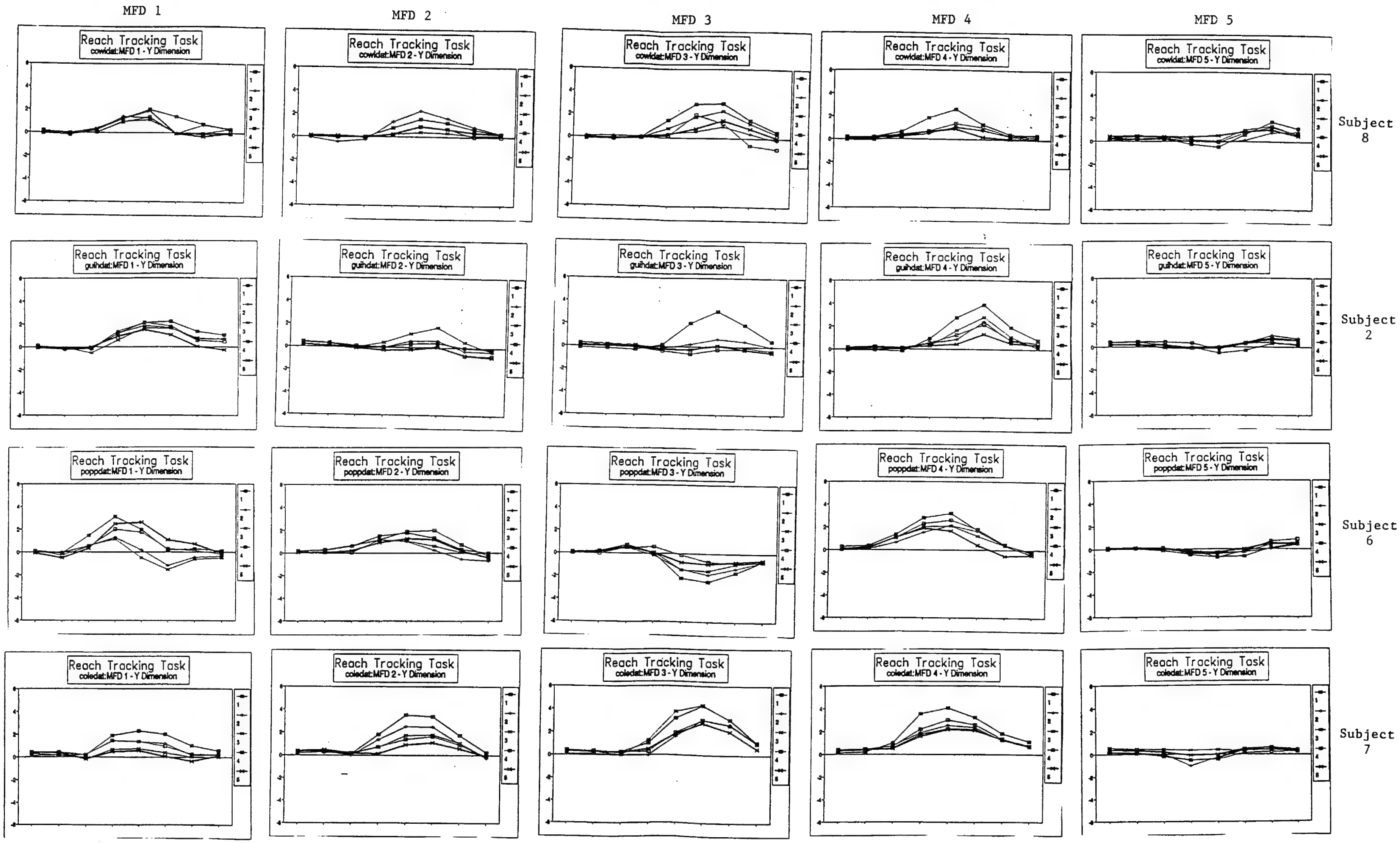


Due to the offset from the center body reference, the resultant data from the x and y axes of The Bird™ are actually combinations of movement within the 2-dimensionally centered body reference of x and y. Thus, it can be expected that patterns of results from the x and y axes may be opposite of what should be found (i.e., the x-axis as obtained from The Bird™ is more representative of the actual centered body reference of y, while the y-axis as reported is more representative of the actual centered body reference of x). This is exactly what was found when the data were analyzed. The z-axis was not affected in this manner.

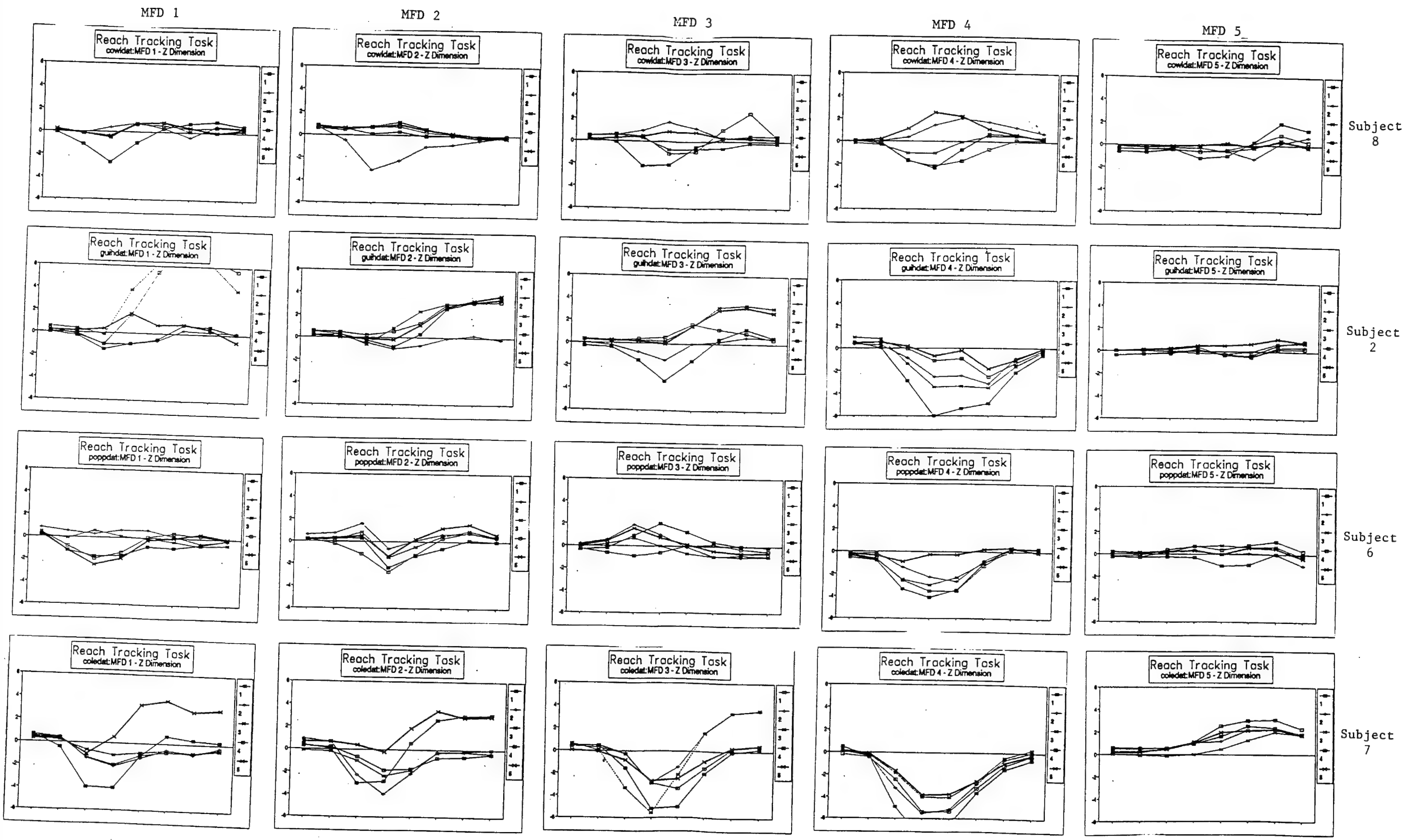
B1. X-Axis Plots of Normalized 3-d Data.



B2. Y-Axis Plots of Normalized 3-d Data.



B3. Z-Axis Plots of Normalized 3-d Data.



APPENDIX C.

Individual Subjective Responses, Design Recommendations, and Anthropometric Measurements

Subject #1 - female

CATEGORY	TYPE	REASON GIVEN
Pain	- right elbow, forearm, and shoulder muscles - neck	- no arm support during keypad task - helmet heavy under g - head tilted downward during keypad task
Disorientation	- dizziness and exaggerated heaviness of body	- twisting to left and leaning forward in seat during MFD task
Fatigue	- neck, from upper back to head - right shoulder	- increased g and task requirements
Weight of Body Parts	- noticeably increased weight of right arm - head very heavy to hold up	- arm weight mostly during keypad task and top button of the MFD task - head heavy most of the time due to increased g

OPINIONS CONCERNING:	DESIGN RECOMMENDATIONS
Seat	- none
Choice Reaction Time Task	- good position of response buttons - could rest arms on legs during task - didn't have to look at response buttons (no head movements up and down between screen and response pad)
Keypad Task	- mount in line of sight to reduce head movements - add arm supports - angle of keypad too severe, reduce angle for more comfortable wrist angle
MFD Reach Task	- the two in the middle and one to the right side was the easiest - one at top and one at far left worse - move in left-most MFD and bring down top-most MFD
Stick, Throttle, and Rudders	- redesign right armrest for flight stick by moving closer to the seat (too far away from side of body)

Weight (lbs)	Stature (cm)	Sitting Height (cm)	Sitting Mid-Shoulder Height (cm)	Bideltoid Breadth (cm)	Right-Hand Thumbtip Reach (cm)
134.5	165.3	88.4	60.3	46.1	74.9

Subject #2 - female

CATEGORY	TYPE	REASON GIVEN
Pain	- back - right tricep	- slumped in seat, seat back angle wrong for these tasks - no right arm support - angle and placement of keypad
Disorientation	- dizziness and tumbling sensation	- leaning forward in seat during MFD task - deceleration period on centrifuge (returning to 1g from +2gz exposure)
Fatigue	- right shoulder and wrist	- increased g and task requirements
Weight of Body Parts	- noticeably increased weight of right arm and fingers (could not rest fingers on buttons or would inadvertently activate) - no control of arm during MFD task - whole-body alignment difficult to maintain in seat	- arm weight mostly during keypad task and MFD task - body out of alignment most of the time

OPINIONS CONCERNING:	DESIGN RECOMMENDATIONS
Seat	- thigh angle too high - need adjustable seat back angle and lumbar support
Choice Reaction Time Task	- more resistance to activate buttons (make buttons harder to push) - too low in lap, move response pad up towards knees
Keypad Task	- move from between knees to beside left knee - add wrist support - angle of keypad too severe, reduce angle for more comfortable wrist angle - buttons too close together, move apart
MFD Reach Task	- avoid leaning forward by removing top MFD - one at lower right easy to reach but must remove right hand from flight stick to activate, place to lower left by throttle - move displays to minimize reach envelope across body and at the top
Stick, Throttle, and Rudders	- none

Weight (lbs)	Stature (cm)	Sitting Height (cm)	Sitting Mid-Shoulder Height (cm)	Bideltoid Breadth (cm)	Right-Hand Thumbtip Reach (cm)
151.3	172.4	87.7	59.0	44.4	73.2

Subject #3 - male

CATEGORY	TYPE	REASON GIVEN
Pain	- mid to lower back, lumbar region - hot spot on top of head	- seat back angle too upright - no liner in helmet
Disorientation	- dizziness and tumbling sensation	- during acceleration and deceleration, but not during plateau +2gz exposure
Fatigue	- none	- none
Weight of Body Parts	- noticeably increased weight of right arm	- arm weight mostly during the MFD task - worse during top and far left MFD reach

OPINIONS CONCERNING:	DESIGN RECOMMENDATIONS
Seat	- recommend 30 degree seat back angle
Choice Reaction Time Task	- none
Keypad Task	- make buttons larger, and move farther apart from each other
MFD Reach Task	- move top MFD down, and bring in the far left MFD towards the middle
Stick, Throttle, and Rudders	- none

Weight (lbs)	Stature (cm)	Sitting Height (cm)	Sitting Mid-Shoulder Height (cm)	Bideltoid Breadth (cm)	Right-Hand Thumbtip Reach (cm)
198.0	177.9	94.0	65.7	54.6	80.0

Subject #4 - male

CATEGORY	TYPE	REASON GIVEN
Pain	- lower and middle back - buttocks - hot spots on top of head and ears	- harness was folded up under back and caused pressure during run - lack of cushion - fit of helmet and increased g over time
Disorientation	- none	- none
Fatigue	- lower and middle back - head and neck	- related to harness fit - heaviness of head and helmet
Weight of Body Parts	- noticeable increased weight of right arm - head very heavy to hold up	- arm weight mostly during keypad task and top button of the MFD task - head heavy most of the time

OPINIONS CONCERNING:	DESIGN RECOMMENDATIONS
Seat	- adjustable cushion on seat pan and at lumbar
Choice Reaction Time Task	- none
Keypad Task	- put keypad on swivel to reduce extreme angle of wrist and forearm
MFD Reach Task	- move displays to minimize reach envelope to left and at the top - don't put something of importance between stick/throttle and MFDs because of inaccuracy of arm/hand movements
Stick, Throttle, and Rudders	- none

Weight (lbs)	Stature (cm)	Sitting Height (cm)	Sitting Mid-Shoulder Height (cm)	Bideltoid Breadth (cm)	Right-Hand Thumbtip Reach (cm)
159.5	174.3	90.7	63.6	47.7	76.5

Subject #5 - male

CATEGORY	TYPE	REASON GIVEN
Pain	- lower back, lumbar region - top of head hurt, like a headache (not a hot spot)	- seat back angle and rudder pedal placement, couldn't scoot completely back into seat - increased weight of head and helmet under +2gz
Disorientation	- dizziness and tumbling sensation	- deceleration period on centrifuge (returning to 1g from +2gz exposure)
Fatigue	- none	- none
Weight of Body Parts	- noticeably increased weight of right arm - no control of arm during MFD task (initially undershot, then adjusted movements)	- increased arm weight during MFD task

OPINIONS CONCERNING:	DESIGN RECOMMENDATIONS
Seat	- make seat back angle more upright - need adjustable seat back angle and lumbar support - need seat cushion for buttocks
Choice Reaction Time Task	- none
Keypad Task	- raise keypad into line of sight to reduce up and down head movements between display and keypad (had to keep head down to see keypad, and tried to move only eyes to see task display)
MFD Reach Task	- lower the top MFD - add more buttons on the MFD to add realism
Stick, Throttle, and Rudders	- stick and throttle positions interfered with knees during +2gz, move throttle and stick away from sides of knees

Weight (lbs)	**Stature (cm)**	**Sitting Height (cm)**	**Sitting Mid-Shoulder Height (cm)**	**Bideltoid Breadth (cm)**	**Right-Hand Thumbtip Reach (cm)**
180.0	174.1	89.2	62.2	48.9	80.9

Subject #6 - male

CATEGORY	TYPE	REASON GIVEN
Pain	- lower back, lumbar region - some right arm muscle soreness	- seat back angle, had to arch back during increased g, wanted to stretch - increased weight of arm under increased g during MFD task
Disorientation	- lightheadedness and some stomach discomfort - after +2gz exposure, felt like I wanted to float away, still had lightheadedness	- during keypad task, had to move eyes up and down while trying to hold head steady - "readaptation" to 1g due to long-term exposure to +2gz
Fatigue	- arm and forearm - neck felt "tight"	- lack of arm support and wrong wrist angle during keypad task - increased weight of head and helmet during +2gz exposure
Weight of Body Parts	- noticeably increased weight of hand and arm - no control of arm during MFD task (initially undershot, then adjusted movements)	- increased arm/hand weight during MFD and keypad tasks

OPINIONS CONCERNING:	DESIGN RECOMMENDATIONS
Seat	- need adjustable seat back angle and lumbar support
Choice Reaction Time Task	- raise button keypad up towards top of knees
Keypad Task	- lower keypad so that arms can rest on legs
MFD Reach Task	- lower the top MFD
Stick, Throttle, and Rudders	- none

Weight (lbs)	**Stature (cm)**	**Sitting Height (cm)**	**Sitting Mid-Shoulder Height (cm)**	**Bideltoid Breadth (cm)**	**Right-Hand Thumbtip Reach (cm)**
187.0	177.8	92.2	64.1	50.4	82.0

Subject #7 - female

CATEGORY	TYPE	REASON GIVEN
Pain	- shoulder blade area on back, extending downward - lower back, lumbar region	- due to reach requirements under +2gz - became worse as time went on due to leaning forward in seat to perform tasks - with no lumbar support, this still may have occurred without the tasks
Disorientation	- feelings of lightness and of falling	- after return to normal 1g (not during +2gz or deceleration)
Fatigue	- forearm - back fatigue	- during keypad tasks, abated between tasks - low level ache throughout +2gz exposure, became worse during MFD task
Weight of Body Parts	- noticeably increased weight of whole body - no control of arm during MFD task (initially undershot/over-shot, then adjusted movements) - head very heavy to hold up	- took more effort to get entire body into desired positions - increased weight of arm/hand under +2gz - head heavy throughout +2gz exposure

OPINIONS CONCERNING:	DESIGN RECOMMENDATIONS
Seat	- need lumbar support and adjustable seat back angle - need cushions on entire seat area
Choice Reaction Time Task	- none
Keypad Task	- move keypad from between the knees to the left of the seat - make buttons easier to push (too much force required to depress number buttons)
MFD Reach Task	- lower the top MFD - move all MFDs closer to the seat - add more buttons on the MFD to add realism
Stick, Throttle, and Rudders	- both stick and throttle need arm rests - stick too far forward from seat

Weight (lbs)	Stature (cm)	Sitting Height (cm)	Sitting Mid-Shoulder Height (cm)	Bideltoid Breadth (cm)	Right-Hand Thumbtip Reach (cm)
118.0	162.0	87.0	60.0	41.2	70.2

Subject #8 - male

CATEGORY	TYPE	REASON GIVEN
Pain	- lower back, lumbar region	- curvature of seat back, no lumbar support
Disorientation	- dizziness and tumbling sensation	- acceleration and deceleration period on centrifuge (not at +2gz plateau)
Fatigue	- right wrist, forearm, and shoulder	- wrong arm angle for the keypad task
Weight of Body Parts	- noticeably increased weight of right arm - head felt heavy	- increased arm weight during all tasks, most noticeably during the keypad and MFD tasks - due to increased g

OPINIONS CONCERNING:	DESIGN RECOMMENDATIONS
Seat	- need adjustable seat back angle and lumbar support - need seat cushions over entire seat area - extend padded seat to sides of knees/legs
Choice Reaction Time Task	- none
Keypad Task	- move closer to body - readjust the angle of the response pad to reduce wrist/forearm discomfort
MFD Reach Task	- lower all MFDs to eye level - bring in all MFDs closer to the seat
Stick, Throttle, and Rudders	- none

Weight (lbs)	Stature (cm)	Sitting Height (cm)	Sitting Mid-Shoulder Height (cm)	Bideltoid Breadth (cm)	Right-Hand Thumbtip Reach (cm)
209.8	184.4	95.2	66.1	53.2	83.9